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SYMPOSIUM ON IMPACT TESTING OF MATERIALS.

PREFACE.

The Symposium on Impact Testing of Materials held at the Twenty-fifth Annual Meeting of the American Society for Testing Materials is the outcome of informal discussion in the Society's Committee E-1 on Methods of Testing extending over a period of nearly two years. It was the consensus of opinion in the committee that steps should be taken by the Society to study the impact testing of materials more definitely and intensely than has heretofore been attempted in any concerted way in this country, considering not only details of methods as they are now in use and the possible standardization of methods and specimens, but inquiring also into the true significance of the impact test, discussing such matters among others as the methods of measuring the resistance of materials to impact stresses and the applicability of the data obtained to problems of engineering design and construction.

Following the review by a special committee of considerable data that had been sent to the Society through the courtesy of the British Engineering Standards Association, Committee E-1 appointed the following committee, which, in cooperation with the Committee on Papers, has planned the present Symposium:

T. D. Lynch, *Chairman*
C. L. Warwick, *Secretary*

E. H. Dix
L. H. Fry
W. H. Fulweiler
F. C. Langenberg
C. E. Margerum
L. J. Markwardt
D. J. McAdam, Jr.
H. F. Moore
E. B. Smith
H. L. Whittemore

The subject has been divided into five main divisions, as indicated in the Table of Contents (page 3), and the aim has been to secure representative papers to cover the several divisions and to serve adequately as an introduction to general discussion which it is hoped will bring out much additional information of value. It is felt that these papers, with the complete discussion, will comprise the most recent and extensive statement of the status of impact testing of materials in this country and will serve as a starting point for the further study of the impact test by the Society which the committee believes is to be desired.

RESUMÉ OF IMPACT TESTING OF MATERIALS, WITH BIBLIOGRAPHY.[1]

By H. L. Whittemore.[2]

Resumé.

For structures under dead load, the usual static tests give the information needed for judging the quality of the material and the allowable stresses for design. With the increase in the speed of machine parts, however, the desire to test a material under conditions approximating actual use, led to impact testing. The specimen, for the sake of convenience, was often supported as a simple beam and struck at the middle of the span by a falling weight. If the material was brittle, it was ruptured provided the energy of the tup was sufficient, but the amount absorbed by the specimen was unknown. If the material was ductile, the specimen was bent and the amount of energy absorbed was indeterminate.

Many ingenious investigators were attracted by the problem of measuring the energy absorbed by the specimen under impact loading and have devised photographic or other apparatus for use with the vertical drop impact machine which draw space-time diagrams for the falling weight while rupturing the specimen or in some other way measure the energy. With the exception of the Hatt and the Fremont machines none of these have come into general use in this country.

By using a pendulum to rupture the specimen, the measurement of the energy absorbed is very much simplified. Knowing the energy available for the position from which the pendulum is released, the final energy can be obtained by observing the height to which it rises after breaking the specimen. The simplicity of the pendulum apparatus and the ease with which the measurements are made, make it suitable for commercial and routine testing and many of the impact machines used in the United States are of that type.

If the energy is to be measured, the specimen must be ruptured under standardized conditions. For this reason, beam specimens are usually notched. The size and shape of the specimen, and especially of the notch, have a great influence upon the results. Many investigations have been made to determine the effect of changing these variables.

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[1] Published by permission of the Director of the U. S. Bureau of Standards.

[2] Mechanical Engineer, Bureau of Standards, Washington, D. C.

In order to obtain a bird's-eye view of the development of impact testing, let us look for a moment at the history of the subject. The impact testing of materials is decidedly modern, more or less coincident with the development of high-speed machinery in general.

As early as 1824, Tredgold discussed from a theoretical standpoint the resistance of cast-iron beams to "impulsive forces," while in 1874 Thurston, from the area of static stress diagrams, computed the impact resistance of materials for a single and for repeated blows. In 1881, the U. S. Board for Testing Iron and Steel published the results of many tests on wrought iron using a drop test machine. Dunn described his photographic drop impact testing machine in 1897, and in the following year Russell came forward with his remarkable pendulum machine adapted for either beam or tensile specimens and gave the results of many tests on engineering materials. This machine had many of the advantages of the Charpy pendulum machine but was apparently used only by Russell himself.

Hatt and Marburg, in 1899, discussed American drop impact testing methods and Keep brought out his machines for cast iron, while Martens, in the American edition of his well-known "Handbook," discussed impact testing in detail. Fremont's drop impact machine was described in 1901, and in the following year Rudeloff discussed, extensively, the influence of the variables on notched bar tests. The Izod pendulum machine appeared in 1903, and in 1904 the Hatt drop machine, the Charpy pendulum machine and the very ingenious Guillery rotary machine appeared. The latter was a radical departure from previous designs. The relative merits of these machines and the value of the results obtained with them were the subject of spirited discussions about this time by such men as Charpy, Breuil and Sir Robert Hadfield.

In 1907, the German Association for Testing Materials adopted Ehrensberger's report standardizing pendulum impact machines of 250, 75 and 10 kgm. and the method of using them. This was followed by Charpy's report to the Fifth Congress of the International Association for Testing Materials, at Copenhagen, 1909.

Many investigators about this time studied the influence of the speed of the striker, the shape and size of the specimen, and of the notch, on the test results.

In 1913-14, Charpy and Cornu-Thenard carried out a test program before a Commission of the International Association to establish the value of the pendulum impact tests on materials and to standardize the apparatus and methods.

BIBLIOGRAPHY.

A more complete survey of the development of this very interesting side of materials testing may be obtained from the bibliography appended hereto.

The bibliography has been prepared to assist those interested in the subject to become acquainted with the careful investigations which have been published by many well-recognized materials engineers.

The effect of impact loading of structures has not been included, as that field is quite a different one.

Although this bibliography is incomplete, it is believed that it contains most of the important papers on the subject in French, German and English. Additional references and corrections will be gratefully received. The notes are intended to guide the reader in choosing references on a particular subject in which he may be especially interested. No attempt has been made to give an opinion upon the value of a paper or the accuracy of the conclusions but, in so far as possible, both sides of a question have been presented. This is desirable because there is still much difference of opinion among materials engineers upon many questions which arise in regard to impact testing.

Credit is due S. N. Petrenko, C. L. Warwick, E. B. Smith and H. A. Anderson for many of the references and for several helpful suggestions which have added to the usefulness of this paper.

APPENDIX.

BIBLIOGRAPHY ON IMPACT TESTING.

For a subject index to this bibliography, see page 33. A chronological index is also included on page 35.

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Anonymous.

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4. "Drop Test for Steel Rails," *Proc.*, Am. Soc. Test. Mats., Vol. II, 1902, pp. 23–42. A discussion on drop tests for steel rails.

5. "Eden Foster Repeated Impact Testing Machine," *Machinery* (London), Vol. 14, April 24, 1919, pp. 105–109. Machine attempts to combine effect of vibration test and impact test by subjecting specimen to both shock and reversal of stress.

6. "Essais de Materiaux a la Traction par Choc," *Genie Civil*, Vol. 45, Oct. 15, 1904, pp. 392–395. Mentions the work of various experimenters and describes machines for shock testing. Gives results of tests on steel and iron with a discussion of the effect of length of specimen, number of blows, speed and temperature.

7. "Force of a Blow," *English Mechanic*, March 11, 1910, p. 119.

8. "How Hard Did It Hit," *Sci. Am.*, Vol. 123, July 10, 1920, p. 44. Description of apparatus used by Dept. Agriculture to measure the resistance of fruit to impact and drop test machine (Hatt-Turner) used in testing airplane woods for impact resistance.

9. "Impact," Report of U. S. Board for Testing Iron and Steel, etc., Vol. 1, 1881, pp. 122–145. Description of a drop test machine having tup weighing 100 lb. and falling 30–50 ft. and the method of making impact tests. The effect of varying the height of drop on the fracture of wrought iron is shown by photographs. The results of many impact tests on contract chain and on hammered and other irons are given.

10. "Impact Stresses," *Engineering*, Vol. 112, July 29, 1921, pp. 189–190.

11. "Impact Testing Machine," *Engineering*, Vol. 89, May 6, 1910, p. 572. Description of the repeated impact machine designed by Dr. Stanton of the National Physical Laboratory.

12. "Machine for Testing Shock Strength of Hardened Steel," *The Engineer*, Aug. 5, 1921.

13. "Military Exhibits at Brussels," *The Engineer*, Vol. 110, July 29, 1910, p. 106. Description of impact testing machines of the Charpy type.

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16. "Impact Test of Fire Brick," *Proc.*, Am. Soc. Test. Mats., Vol. XVI, Part II, 1916, pp. 366–367. Describes an impact test made on fire brick by means of a falling weight. No test results are included.

17. "Neuere Materialprüfungsmaschinen," *Stahl und Eisen*, Vol. 26, June 1, 1906, p. 693. Description of the Guillery impact machine.

18. "The Methods of Notched Bar Impact Testing," Report on Engineering Department for year ending March 31, 1915, made by Supt. to Director, National Physical Laboratory Report for year 1914–1915, pp. 98–99. Discusses progress on program for Eng. Standards Com. given in report for year 1913–1914.

19. "Notched Bar Test Pieces," British Eng. Standards Assoc., *Report No. 131*, 1920, pp. 1–15. Specimens to be fractured by single blow, any machine. Striking energy and velocity given for Charpy, Izod, Fremont, Amsler and Guillery. Results not materially different if striking velocity is more than 3 m. per sec., but results should only be compared if dimensions of the specimen are identical. Express in metric units. Give average of three tests. British standard specimen, 10 by 10 mm. in section with V notch of 45 deg. angle, depth 2 mm. and one quarter millimeter radius at bottom of the notch. If necessary specimens 10 by 5 mm. or 5 by 5 mm. can be used. Dimensions of supports and strikers are given for both beam and cantilever type of specimen.

20. "Pittsburgh Continuous and Alternating Impact Testing Machine," *Am. Mach.*, Vol. 54, March 17, 1921, p. 480. Describes a machine for testing metals by repeated blows of a ram which drops vertically.

21. "Resilience," *Rev. Met.*, Vol. 9, 1912, pp. 1174–1181. Description of a drop impact machine for notched specimens with means for measuring the kinetic energy of the striker after rupturing the specimen and the variation in the resilience of the metal. The effect of height of drop is negligible when not more than twice that required to break the specimen but the resilience decreases when the weight of striker is increased. The notch influences the results.

22. "Report of Committee D-10 on Shipping Containers," *Proc.*, Am. Soc. Test. Mats., Vol. XVI, 1916, pp. 349–356. Describes a method of testing boxes in a rotating drum.

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26. "Standard Method of Test for Toughness of Rock," adopted 1908, revised 1918, *A.S.T.M. Standards*, 1921, pp. 711–712. This method was approved March 28, 1921, as a "Tentative American Standard" by the Am. Eng. Standards Com.

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28. "Testing Steel for Automobile Parts," *Machinery*, Vol. 19, Oct., 1912, p. 118. Describes the experience of G. Derihon with Fremont drop machine and the improvement in the product that resulted from its use.

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32. "Work of the Royal Technical Institution," *Zeit. Werkzeugmaschinen*, Vol. 6, p. 153.

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"La Fragilite des Metaux et les Essais au Choc," *Technique Moderne*, Vol. 1, Dec., 1909, pp. 590–594; Vol. 2, Jan., 1910, pp. 14–19. Summary of the official report for the Congress at Copenhagen, 1909, of the International Association for Testing Materials and the other reports with discussions. First part, the reports of other committees on impact are referred to briefly and Ehrensberger's conclusions given. Fragility, resilience and specific work of rupture are described, also the relation between tests producing the same deformation slowly and by shock. Second part, the following subjects are considered: what conditions must be satisfied for shock tests? do flexural tests of notched specimens of metal furnish indications not obtainable from other tests? is there a relation between the results of impact tests of notched specimens and the way they behave in service? The conclusions are given.

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"Sur l'influence du Temps dans des Deformations Rapides des Metaux," *Comptes Rendus*, Vol. 158, 1914, pp. 1969–1973. Their tests show the value of impact tests of notched bars as the variables likely to occur have little influence on the results.

Charpy, G., and Cornu-Thenard, A.

"Sur les Essais de resilience," *Comptes Rendus*, Vol. 164, 1917, pp. 473–477; *Chem. and Met. Eng.*, Vol. 17, 1917, pp. 397–407. Results of impact tests made before a Commission of International Association for Testing Materials. Conclusions: The influence of height of fall is negligible under usual conditions; apparatus of different dimensions or of different types but well made and accurately calibrated give concordant results; the influence of the notch is considerable, the value found for the resilience diminishes when the depth of the notch is increased, other things being equal.

"Note sur un Procede de Tarage des Appareils d'Essais des Metaux par Choc," *Rev. Met.*, Vol. 10, 1913, pp. 1233–1238. The results of this investigation on pendulum machines leads to the conclusion that impact specimens without notches give practically identical results. If specimens of this kind are prepared with suitable precautions they may be used to verify impact machines.

"Nouvelles Experiences sur les Essais de Choc et la Determination de la Resistance," *Rev. Met.*, Vol. 14, 1917, p. 84–122. Describes a careful investigation of the variables which may occur in impact testing with the results of tests and descriptions of the Charpy pendulum machine.

"New Experiments on Shock Tests and on the Determination of Resilience," *Jour.*, Iron and Steel Inst., Vol. 96, Part 2, 1917, pp. 61–119. Description of Charpy impact machine and of an elaborate investigation of impact resistance of steel with comparisons with results obtained with the Guillery and the vertical drop machine. The type of notch, size of specimen and the application of the law of similarity are carefully considered.

Coker, E. G.

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Cornu-Thenard, A. See Charpy, G.

"Sur les Essais de Flexion par Choc de Barreaux Entailles," *Comptes Rendus*, Vol. 168, 1919, pp. 1315–1318. Results of tests on notched beam specimens.

Different materials tested by impact and by slowly applied loads show little difference in the work required to rupture. For most steels therefore the speed of the striker has little effect on notched bar impact tests.

Compte Rendus, Vol. 169, 1919, p. 272. It is concluded that it is advisable to give to the notch (1) sufficiently small diameter, maximum recommended being 2 mm. for a 10 by 10 mm. bar and (2) sufficiently large depth, one half the depth of the bar being suggested as advisable practice.

Davidenkoff, N.

"Investigation on the Theory of a Tensile Impact Tester and Its Errors," Int. Assoc. Test. Mats., IV-7, VI Cong., New York, 1912, pp. 1-14; "Étude sur la Theorie d'un Appareil de Choc par Traction," *Rev. Met.*, Vol. 9, 1912, pp. 1184-1188. Description of a drop impact machine and some results of tests. To avoid large errors the speed of the tup should be measured immediately after fracture of the specimen.

Denis, M.

"Étude sur les Proprietes Generales des Aciers a Outils," *Rev. Met.*, Vol. 11, 1914, pp. 569-669. The results of an extensive investigation of the properties of tool steels giving chemical analysis, impact hardness, etc. Tests were made at high and low temperatures.

Derihon, M.

"Notes on the Brittleness Test," Int. Assoc. Test. Mats., IV-3, VI Cong., New York, 1912, pp. 1-5; *Mech. Eng.*, Vol. 31, Jan. 17, 1913, pp. 64-65. Relates experience with Fremont machine in testing 10,000 to 12,000 steel specimens per month and by perfecting methods of heat treatment reducing rejections from 20 to 40 per cent to a negligible number.

"Quelques Observations a Propos de l'Essai de Fragilite," *Rev. Met.*, Vol. 9, 1912, pp. 1167-1170. From experience, the author concludes that a test for fragility should be used for the acceptance of steel. He prefers Fremont's small specimen and considers the anvil and the speed of the striker of great importance.

Dick, T. S.

"Impact Testing," Rugby Eng. Soc., Nov., 1905.

Diederichs, H.

See Carpenter, R. C.

Dilber, G., and Hannover, H. T.

"Methods of Testing," *Jernkontorets Annaler*, Vol. 42, pp. 126-152; *Injenioren*, 1907, pp. 162-177, 169-174.

Dix, E. H., Jr.

"The Single Blow Notched Bar Impact Test as Used in the American Industry," *Proc.*, Am. Soc. Test. Mats., Vol. 19, Part II, 1919, pp. 720-756. Describes the Olsen, Izod and Charpy pendulum impact machines and gives comparative data obtained with them.

"Charpy Impact Test as Applied to Aluminum Alloys," *Min. Met.*, No. 160, April, 1920, pp. 1-16. Results of tests on aluminum alloys, description of methods and apparatus.

Dudley, P. H.

"Elongation and Ductility Tests of Steel Rail Sections under the Manufacturers' Standard Drop Testing Machine," *Proc.*, Am. Soc. Test. Mats., Vol. X, 1910, pp. 223-232. Discussion of the results obtained with the Manufacturers' drop testing machine on steel rails. Includes values for ductility and elongation of rails.

Dunn, B. W.

"A Photographic Impact Testing Machine," *Jour.*, Franklin Inst., Vol. 144, Nov., 1897, pp. 321–348; Discussion, *Jour.*, Franklin Inst., Vol. 145, Jan., 1898, pp. 36–47, Description of apparatus for the dynamic measure of pressure produced by a blow, with details of time and distance measuring mechanism. Curves obtained with the apparatus are shown and empirical formulas for the maximum resistance given.

"Measurement of Impact Stresses," *Proc.*, Am. Soc. Test. Mats., Vol. IX, 1909, pp. 644–651. A description of impact tests on railroad cars by means of a hydraulic apparatus and by means of a dynamometer. Some results are given for various speeds of car.

Edwards, A. C., and Willis, F. W.

"A New Method of Testing Hardness," *The Engineer*, Vol. 126, Aug. 16, 1918, p. 142. Describes a drop impact apparatus for measuring hardness of metals by indenting them with a 10-mm. steel ball and measuring the indentation.

Ehrensberger, H. C.

"Die Kerbschlagprobe im Materialprüfungswesen," Report adopted by German Assoc. for Test. Mats., Berlin, Oct. 5, 1907, *Zeit.*, Ver. Deut. Ing., Vol. 51, Dec. 14, 1907, pp. 1974–1982; Dec. 28, 1907, pp. 2065–2070; *Stahl und Eisen*, Vol. 27, Dec. 11, 1907, pp. 1797–1809; Dec. 18, 1907, pp. 1833–1839; *Rev. Met.*, April, 1908. Description of pendulum impact machines of 250, 75 and 10 kgm. and results of tests, including impact, on carbon, nickel, chrome-nickel, special and cast steel. Circular and rectangular impact specimens having triangular notches of several sizes were tested. Low temperatures (−35° C.) showed a decrease in the impact resistance.

Elliott, H. A.

"The Importance of the Impact Test," *Trans.*, Soc. Automobile Engr., Vol. 10, Part 1, 1915, pp. 298–302. Emphasizes importance of impact tests which are much used in Europe. Quotes Prof. Guillet and Mr. Derihon. Gives data obtained by the latter showing decrease in rejections as heat treatment was improved. The Fremont hammer was used and Nusbaumer's recommendation that the angle and character of fracture be observed was adopted after trial.

Elmendorf, A.

"Stresses in Impact," *Jour.*, Franklin Inst., Vol. 182, 1916, pp. 771–790. Theoretical discussion of impact and results of experiments on Hatt-Turner drop impact machine on timber beams.

Endsley, L. E.

"Impact Between Freight Cars in Switching Service," *Ry. Rev.*, Vol. 57, July 3, 1915, pp. 10–13. From a paper before Ry. Master Mechanics Assoc. Describes tests of impact in switching cars and the chronograph used. Results of tests are given.

Ensaw, H.

"The Impact Test of Materials," *Mech. World*, Vol. 62, Nov. 2, 1917, p. 246. Very general discussion of impact testing with diagram of the Stanton repeated impact machine.

Fereday, H. J.

"Impact Testing Suggestions," "Impact Tests and Allowances," *Engineering*, Vol. 112, July 8, 1921, pp. 50 and 80; Vol. 132, July 15, 1921, p. 59. Sug-

gestions for conducting future tests in order to obtain, if possible, new formula for impact effect. Paper read before Inst. Civ. Engr.

Fereday, H. J., and Palmer.

"Impact Stress Recorder," "Fereday and Palmer's Patent Stress Recorder," *Ry. Gaz.*, Vol. 35, Aug. 12, 1921, pp. 283–285. Describes an instrument for recording impact stresses on railway bridges by a train passing at high speed.

Forrest, C. N.

See Richardson, C.

Freminville, C. de.

"Caracteres des Vibrations Accompagnant le Choc," *Rev. Met.*, Vol. 4, 1907, pp. 833–884. An extensive discussion of the fracture in different materials caused by shock with many illustrations and diagrams.

"Reliability of Materials and Mechanisms of Fractures," *Trans.*, Am. Soc. Mech. Engr., Vol. 41, 1919, pp. 907–923; *Chem. and Met. Eng.*, Vol. 22, May 26, 1920, pp. 983–987. A discussion of the differences between the behavior of material under test and in service which can be explained by an analysis of the mechanism of fracture. The laws of fracture can be formulated. Consideration is given to the design of members so that the stresses do not conflict with the laws of mechanism of fracture.

Fremont, C.

"Essai des Metaux par Pliage de Barrettes Entaillées," *Bul.*, Soc. Encouragement Industrie Nationale, Vol. 101, Part 2, Sept., 1901, pp. 365–389. Describes the Fremont drop impact machine and methods of testing steel with the results of tests to show the influence of shape of notch and dimensions of specimen.

"The Testing of Metals by Impact on Notched Bars," Int. Assoc. Test. Mats., IV–2, VI Cong., New York, 1912, pp. 1–5; *Rev. Met.*, Vol. 9, 1912, pp. 1163–1166. A discussion of Charpy's report on notched bar impact tests which was adopted by the Congress at Copenhagen, 1909, by the International Association. The choice of apparatus, the dimensions of the specimen, the form of the notch and the results of his own experience are considered.

Fuller, S. B., and Johnston, W. A.

Applied Mechancs, Vol. 1, Wiley and Sons, New York, 1913. "Impact," pp. 347–362. Theoretical discussion with problems.

Gagarine, A.

"Automatic Impact Stress-Strain Recorders," Int. Assoc. Test. Mats., IV–8, VI Cong., New York, 1912, pp. 1–24; *Rev. Met.*, Vol. 9, 1912, pp. 1189–1207. Description of a drop impact machine with means for measuring the force exerted on the specimen by the deformation of the anvil which is a heavy steel tube. Curves and the results of tests are given.

Gessner, A.

"Diagrams of Impact Tests," *Zeit.*, Ost. Ver., Vol. 58, 1907, p. 665.

"Über Schlagproben mit Gusseisen," *Stahl und Eisen*, Vol. 30, Aug. 10, 1910, pp. 1367–1369. Results of tests to show the relation between static and impact tests on cast iron.

"Nicked Bar Impact Tests on Tough Steels," Int. Assoc. Test. Mats., IV–4, VI Cong., New York, 1912, pp. 1–7; *Rev. Met.*, Vol. 9, 1912, pp. 1171–1173. From experiments on notched bar impact specimens of tough steel it was found that the type of rupture causes 50 per cent difference in results. The results are also affected by the edge on the pendulum, this causing differences as great as 25 per cent.

"Über Schlagbiegeproben mit Gusseisen," *Stahl und Eisen*, Vol. 35, July 29, 1915, pp. 769–773. Results of impact tests on cast iron with comparison of static and dynamic tests.

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"Fatigue and Impact Fatigue Tests of Aluminum Alloys," *Proc.*, Am. Soc. Test. Mats., Vol. XX, Part II, 1920, pp. 115–136. Describes Stanton type of impact fatigue machine and some results obtained on aluminum alloys.

Giesen, W.

"Hardness Impact Tests of Special Steels," Iron and Steel Inst., Vol. 1, 1909, p. 19.

Glen, J. S.

See Primrose, H. S.

Goldberg, G.

"Necessity of Impact Tests," *Giesserei Zeit.*, Vol. 6, p. 609.

Gooch, E. P.

"Impact Testing," *Elec. Jour.*, Vol. 15, Oct., 1918, pp. 403–404. Description of a vertical drop impact testing machine for testing machine parts such as railway motor shafts.

Goss, W. F. M.

"The Master Car Builders' Drop Testing Machine as Installed at Purdue University," *Proc.*, Am. Soc. Test. Mats., Vol. III, 1903, pp. 256–261. A complete description of the M. C. B. drop testing machine, including a historical outline of the drop test and a description of the method of testing couplers, draft gears, etc.

Greaves, R.

See Jones, R. M.

Greaves, R. H.

"Temper Brittleness of Nickel-Chrome Steel," *Jour.*, Iron and Steel Inst., Vol. 100, Part 2, 1919, pp. 329–351. Results of tests, including impact, showing that impact tests do reveal temper brittleness caused by slow-cooling from tempering temperature, while static tests do not.

Greaves, R. H., and Moore, H.

"Notes on the Single Blow Impact Test on Notched Bars," *Proc.*, Inst. Civ. Engr., Dec., 1920.

Grent, L.

"Calcul du Travail de Choc que Peuvent Supporter Quelques Eprouvettes," *Rev. Met.*, Vol. 6, 1909, pp. 835–841. Mathematical discussion of the work required to rupture specimens loaded by impact, either axially, or as beams.

Guillery, M.

"Nouvelle Methode d'Essais Mecaniques des Metaux," *Rev. Met.*, 1904, p. 405. Description of the Guillery rotating disk impact machine with a discussion of the errors and method of using it.

Guillet, L.

"Some Repeated Impact Tests," *Rev. Met.*, Feb., 1921, p. 96. For high resistance to impact, the resilience must be combined with high elastic limit.

"New Experiments on Repeated Impact Test," *Rev. Met.*, Dec., 1921, p. 755.

Guillet, L., and Revillon, L.

"Impact Tests at Variable Temperatures," Int. Assoc. Test. Mats., III-4, V Cong., Copenhagen, 1909, pp. 1-5. Results of tests on blue heat brittleness on carbon, nickel and nickel-chrome steel using the Guillery machine. The variation of temperature with impact resistance is given for the conditions investigated.

"Application of Modern Testing Methods to Copper Alloys," Int. Assoc. Test. Mats., III-6, V Cong., Copenhagen, 1909, pp. 1-5. Results of tests, including impact, on copper alloys with discussion.

Hackstroh, P.

See Snyders, J.

Hadfield, Sir R. A.

"Unsolved Problems in Metallurgy," *Proc.*, Inst. Civ. Engr., Vol. 166, 1906. Tests, p. 215. Illustration of need for impact test to show brittleness of steel which was not shown by tensile test.

Hadfield, Sir R. A., and Main, S.

"Shock Tests and Their Standardization Including the Effect of High Velocities of Impact up to 2870 ft. per sec.," *Proc.*, Inst. Civ. Engr., Dec., 1920.

Hall, J. H.

"Shock Tests on Cast Steel," *Bul.*, Am. Inst. Min. Engr., 1913, pp. 1247-1256. Results of tests of cast steel with the Fremont machine and a comparison with tensile and other tests.

Hannover, H. T.

See Dilber, G.

Harboard, F.

"Different Methods of Impact Testing on Notched Bars," *Proc.*, Inst. Mech. Engr., Nov., 1908, Parts 3 and 4, pp. 921-1022. Description of methods of tests used by Fremont, Izod, Seaton, and Jude, Brinnell, Kirkaldy, with discussion of the variation using duplicate specimens. The relation between carbon content and impact values is given with the results of tests on overheated, on restored, and on many commercial steels.

Hatfield, W. H.

"The Mechanical Properties of Steel with Some Consideration of the Question of Brittleness," *Proc.*, Inst. Mech. Engr., 1919, Part 1, pp. 347-533. Discussion of impact tests on notched specimens as well as other tests and gives some results. An eight page bibliography is included.

Hatt, W. K.

"Impact Tests of Iron and Steel at Purdue University," *Eng. News*, Vol. 45, Jan. 3, 1901, pp. 82-83. Results of impact tests on steel wire and Norway iron, machine steel and nickel steel.

"Tensile Impact Tests of Metals," *Proc.*, Am. Soc. Test. Mats., Vol. IV, 1904, pp. 282-315. A description of drop machine for making tensile impact tests. The energy required for rupture is determined from a record of the path of the falling hammer. The results of experiments on steel wire show the relation between static and impact tensile tests.

Hatt, W. K., and Marburg, E.

"Preliminary Report on Present State of Knowledge Concerning Impact Tests," Am. Sec. Int. Assoc. Test. Mats., *Bul. No. 5*, Oct., 1899, pp. 27-50;

Eng. News, Vol. 45, Jan. 3, 1901, pp. 14–16. General discussion on impact testing and also American commercial impact tests for axles, car wheels, rail, cast iron couplers and the corresponding German tests.

"Bibliography on Impact Tests and Impact Testing Machines," *Proc.*, Am. Soc. Test. Mats., Vol. II, 1902, pp. 283–297. The final report of the committee of the American Section of the International Association, transmitting a thirteen page bibliography which includes titles of articles on impact in English, French and German.

Hatt, W. K., and Turner, W. P.

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Heyn, E.

See also Martens, A.

"Die Kerbwirkung und ihre Bedeutung für den Konstrukteur," *Zeit.*, Ver. Deut. Ing., Vol. 58, March 7, 1914, pp. 383–391. Discussion of the effect of notches on the stress in a specimen with illustrations of the behavior of specimens of different materials and shapes under load.

"New Photo-elastic Experiments on the Influence of Notch on Stresses," *Stahl Eisen*, 1921, pp. 541, 611.

Hinrichsen, F. W.

See Martens, A.

Honiger, W.

"Anwendung der Kinematographie zur Ermittlung der Stosskraft bei Schlagversuchen," *Zeit.*, Ver. Deut. Ing., Vol. 56, Sept. 14, 1912, pp. 1501–1505. Description with drawings of a photographic apparatus for obtaining a curve showing the behavior of specimens under impact.

Howe, H. M.

"The Resilience Test," *Chem. and Met. Eng.*, Vol. 17, Sept. 15, 1917, pp. 298–300. A discussion of the type of machine and the form of specimen, nicked or unnicked, giving the most trustworthy measure of the resilience of a metal. Proposes a threaded specimen. Suggests an investigation of: 1. Can either the nicked or the unnicked test be made to give trustworthy results of fitness for both nicked and unnicked impact service? 2. With materials of such a degree of heterogeneousness as ought to be provided for, can a single nicked test piece give a trustworthy measure of resilience? 3. If not, is it more expedient to substitute a 2-in. threaded length of impact tensile test piece for the single nick, or to test for each material so large a number of test pieces as to insure detecting approximately the weakest section?

Hubert, H.

"Present Methods of Testing," *Jour.*, Iron and Steel Inst., Vol. 88, Part 2, 1913, pp. 203–225. Discussion of methods of making impact tests and the arguments for and against the value of these tests in determining the value of metal for engineering uses. Outlines the work of the Int. Assoc. Test. Mats. on impact tests.

Izod, E. G.

"Pendulum Apparatus for Testing Steel as Regards Brittleness," British Assoc. for Advancement of Sci., Sec. G, 1903, pp. 787–788; *Engineering*, Vol. 76, Part 1, Sept. 25, 1903, p. 418; pp. 431–432. Description of the Izod pendulum impact machine and some results on steel and brass.

Jackson, F. H., Jr.

"Effect of Controllable Variables on the Toughness Test for Rock," *Proc.*, Am. Soc. Test. Mats., Vol. XVII, Part II, 1917, pp. 573–588. Title clearly indicates the material covered.

Johnson, J. B.

Materials of Construction, Wiley and Sons, New York, 1897; "The Resilience of Materials," pp. 75–86; "Theory, Impact and Hardness Tests," pp. 375–383; "Comparison of Tension, Impact and Cold Bending Tests," pp. 403–406; "Effect of Temperature on Resistance to Impact," pp. 564–565.

Materials of Construction, Wiley and Sons, New York, 1918; "Resilience," pp. 38–41; "Theory, Impact Testing Machines," pp. 65–66; "Impact Tests," pp. 124–127; "Shock Resistance of Cast Iron," p. 715; "Effect of Temperature on Resistance of Iron and Steel to Impact," p. 763.

Johnston, W. A.

See Fuller, S. B.

Jones, R. M., and Greaves, R.

"The Effect of Over-Strain on the Impact Figure of Steel," *Proc.*, Inst. Civ. Engr., Dec., 1920.

Jungst, C.

"Beitrag zur Untersuchung des Gusseisens," *Stahl und Eisen*, Vol. 33, Aug. 28, 1913, pp. 1425–1433. Gives the results with discussion of tests on cast iron, including pendulum and drop impact tests.

Keep, W. J.

"Impact," *Trans.*, Am. Soc. Mech. Engr., Vol. 21, 1899–1900, pp. 369–395. Describes a pendulum and a drop impact machine, also a transverse testing machine having autographic attachments. The results of calibration tests on bars of spring tempered, tool steel of various sizes are given.

Kirkaldy, W. G.

See Blount, B.

Kreuger, H.

"Apparat zum Messen von Stossen," *Bauingenieur*, Vol. 2, Feb. 28, 1921, pp. 103–106. Suggests measuring the force of impact by observing the impression made by a spherical surface in a polished plate both being of chrome steel and comparing with the impression made under known loads. A theoretical discussion with many details of application is given.

Kuhlmann, E.

"Die Beurteilung der Kerbschlagprobe," *Zeit.*, Ver. Deut. Ing., Vol. 66, Jan. 14, 1922, p. 43. Experiments showing that the energy absorbed by the specimen, per unit of cross-sectional area of specimen decreased with increase of width of the specimen for carbon and nickel steel. However, the energy per unit of volume of the specimen affected is constant for widths from 1 to 3 cm. The volume is computed by observing the stress lines on a polished surface. A direct relation was observed between this impact value and the contraction of area for tensile specimens.

Langenberg, F. C.

"Experimental Data Obtained on Charpy Impact Machine," *Trans.*, Am. Inst. Min. Met. Engr., Vol. 62, 1920, pp. 436–470; *Chem. and Met. Eng.*, Vol. 21, Oct. 8, 1919, p. 461; Vol. 22, Feb. 18, 1920, pp. 325–327. Description of Charpy impact machine and specimens. Results of tests including impact on chrome-nickel steel forgings are given with a discussion of the value of the impact test in obtaining forgings suitable for ordnance work. Discussion by Zimmerman gives theory and operation of the tensile impact machine devised by Lewis. A falling weight breaks the specimen, drawing a time-space curve on a revolving drum. From this the load on the specimen can be obtained by a "protractor" which has been devised for the purpose.

"Impact Tests on Cast Steel," *Proc.*, Am. Soc. Test. Mats., Vol. 21, 1921, pp. 840–851. Contains the results of an investigation to determine: (1) the effect of phosphorus on converter cast steel, (2) the effect of carbon and manganese on cast steel made in a 3-ton basic electric furnace, (3) the effect of heat treatment on acid open-hearth cast steel, (4) the comparative impact resistance of forged steel with those obtained above.

Lanza, G.

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"Report of Committee K on Standard Methods of Testing," *Proc.*, Am. Soc. Test. Mats., Vol. 6, 1906, pp. 102–106. A questionnaire is given which was sent to testing laboratories in different parts of the world. Those on impact are given on p. 105.

Leber, E.

"Über den Gegenwärtigen Stand der Schlagbiegeprobe mit Eingekerbten Staben," *Stahl und Eisen*, Vol. 27, July 31, 1907, pp. 1121–1125; Aug. 7, 1907, pp. 1160–1164. A summary of impact testing with references to principal experimenters in this field and the results of their work.

LeChatelier, A.

"Influence du Temps et de la Temperature sur les Essais au Choc," *Rev. Met.*, Vol. 6, 1909, pp. 914–917. Discussion of the influence of time and temperature on the results of impact tests.

Legrand, M.

"Notched Bar Tests," *Rev. Met.*, April, 1921, p. 225.

Leitzmann, F.

"Eine Aufgabe aus der Stosselastizität und Festigkeit," *Zeit.*, Ver. Deut. Ing., Vol. 44, March 31, 1900, pp. 417–420; April 21, 1900, pp. 514–517. A mathematical discussion of the elasticity and strength of steel under impact.

Leon, A., and Ludwik, P.

"Comparative Static and Dynamic Notched Bar Bending Tests," Int. Assoc. Test. Mats., III–7, V Cong., Copenhagen, 1909, pp. 1–2. Very brief description of the tests showing specimens and some of the conclusions.

"Essais Comparatifs de Flexion Statique et Dynamique sur Barreaux Entailles," *Rev. Met.*, Vol. 7, 1910, pp. 117–122. A comparison of the results on notched impact specimens of steel with conclusions on the influence of form of notch, etc.

Levy, H.

See Perot, A.

Longmuir, P.

"The Corrosion of Metals," *Jour.*, Iron and Steel Inst., Vol. 83, Part 2, 1911, pp. 147–169. The results of tests in Arnold's alternating stress machine are given on p. 160 for some of the steels. None of these exceed 350 alternations.

Ludwik, P.

See Leon, A.

McAdam, D. J., Jr.

"Endurance and Impact Tests of Metals," *Proc.*, Am. Soc. Test. Mats., Vol. XVI, Part II, 1916, pp. 292–308. Describes a method of impact testing developed at the U. S. Naval Engineering Experiment Station, Annapolis, Md. This consists of the shearing of an unnicked specimen by a swinging pendulum. Gives results of tests, including impact, and also fatigue, on iron, carbon, nickel, chrome-nickel steel, monel metal, copper, etc.

"Tests for Endurance and Impact," *Iron Trade Rev.*, Vol. 59, Dec. 21, 1916, pp. 1257–1260. Paper at nineteenth meeting of Am. Soc. Test. Mats. Describes McAdam impact shear apparatus for metals and the results of tests, including impact and torsional fatigue tests, on iron, carbon, nickel and nickel-chrome steel.

McGarvey, Cline.

"Forest Service Tests to Determine the Influence of Different Methods and Rates of Loading on the Strength and Stiffness of Timber," *Proc.*, Am. Soc. Test. Mats., Vol. VIII, 1908, pp. 535–540. The autographic and automatic drop impact testing machine used by the Forest Service is described on p. 538.

McWilliam, A., and Barnes, E. J.

"A Heat Treatment Study of Bessemer Steels," *Jour.*, Iron and Steel Inst., Vol. 79, Part 1, 1909, pp. 348–382. Some discussion but no description of Arnold's alternating stress machine.

Macgregor, J. S., and Stoughton, B.

"A New Method of Testing the Endurance of Case-Hardened Gears and Pinions," *Proc.*, Am. Soc. Test. Mats., Vol. XI, 1911, pp. 822–832. Describes an impact test made on material cut from case-hardened gears and tested in a Fremont machine. No test values are included.

MacLachlan, D. R.

"A New Impact Testing Machine," *Engineering*, Vol. 90, Dec. 23, 1910, pp. 860–861. Description of vertical drop impact tensile test machine with means for drawing a time-displacement curve on a rotating drum.

Magruder, W. T.

"Supports for Beams in Tests of Transverse Strength," Paper for forty-eighth meeting Am. Assoc. Advancement of Sci., *Eng. News*, Vol. 43, Jan. 11, 1900, p. 18. Discusses supports for beams in static tests which should prove helpful in designing beams for impact tests.

Main, S.

See Hadfield, Sir R. A.

Marburg, E.

See Hatt, W. K.

Margerum, C. E.

"A Test for Shock Strength of Hardened Steel," *Proc.*, Am. Soc. Test. Mats., Vol. 21, 1921, pp. 876–882. Contains a description of a new impact machine which measures the force, rather than the energy, by the indentation of a record bar by a hardened steel ball.

Martens, A.

Handbook of Testing Materials, Wiley and Sons, New York, 1899, "Resistance to Impact," pp. 203–256. Description of machines and discussion of speed, shape of specimen, methods of testing, etc.

Martens, A., and Heyn, E.

Handbuch Materialienkunde für den Maschinenbau, Zweiter Teil, Julius Springer, Berlin, 1912. "Die Kerbwirkung," pp. 364–369. Discussion of stress distribution in notched specimens, (1) Die Kerbzugprobe, pp. 369–376. Theory of stress distribution in notched tensile specimens with results of tests. (2) Kerbbiegeprobe bei verschieden grosser geschwindigkeit der die Biegung bewirkenden Krafte, pp. 376–378. The effect of speed on the results. (3) Die Kerbschlagproben, pp. 378–399. Methods of making notched impact tests with description of Guillery and Charpy type machines, influence of form of notch, dimensions of specimens, and value of the impact test are discussed.

Martens, A., and Hinrichsen, F. W.

Das Materialprüfungswesen, Enke, Stuttgart, 1912. "Dynamische Versuche —Der Schlagversuche," pp. 50–52. Short outline of notched impact testing.

Martin, S. S.

"Some Results Showing the Behavior of Rails under the Drop Test, and Proposed New Form of Drop Testing Machine," *Proc.*, Am. Soc. Test. Mats., Vol. VIII, 1908, pp. 128–142. Title clearly indicates the material covered.

Mattimore, H. S.

"Wear Resisting Values of Various Aggregates for Concrete Roads Indicated," *Eng. News Record.*, Vol. 80, May 2, 1918, pp. 861–863. Specimens of concrete, 6 in. cubes. Upper surface subject to impact of a tilting hammer carrying several "hitting points" formed of calks for horse shoes. The specimen is rotated. Results shown on concrete and paving brick.

"Impact Test on Concrete to Regulate Coarse and Fine Aggregate Qualities and Mixes for Highways," *Proc.* Am. Soc. Test. Mats., Vol. XX, Part II, 1920, pp. 266–276.

Memmler, K.

Materialprüfungswesen, Sammlung Goschen, Leipzig, 1907, "Mit stossweiser Belastung (Schlagversuch)," pp. 86–99. Brief description of impact machines, both pendulum and drop, with methods of testing.

Merriman, M.

"The Resistance of Materials Under Impact," *Eng. News*, Aug. 16, 1894. Address before Am. Assoc. Advancement of Sci. History of impact testing, with suggestions as to lines for future work.

The Strength of Materials, Wiley and Sons, New York, 1897, "Resilience of Materials," pp. 105–113. Theoretical discussion.

Milton, J. T.

"Fractures in Large Steel Boiler Plates," *Trans.*, Inst. Naval Arch., Vol. 47, Part 2, 1905, pp. 357–391. Results of tests, including repeated impact or fatigue tests, upon English and American boiler plate.

Mimey, M. A.

"Les Causes d'Erreurs dans les Essais de Choc et la Motion de Fragilite," *Rev. Met.*, Vol. 10, 1913, pp. 1239–1256. A discussion of the errors which may occur in impact testing with mathematical analysis of the force exerted on the

fragments of the specimen and the motion imparted to them, work of deforming the striker and supports, and the rise in temperature of the specimen.

"Note on Shock Tests," *Rev. Artillerie*, July, 1916.

Moore, H.

See Greaves, R. H.

Morean, G.

"Researches on the Duration of Impact," *Annales de Physique*, Vol. 14, Nov., Dec., 1920, pp. 306–333. Measurements of duration of impact between ball and plane by electrical process and empirical formula for calculating it.

Newlin, J. A., and Wilson, T. R. C.

"The Development of a Box-Testing Machine and Some Results of Tests." *Proc.*, Am. Soc. Test. Mats., Vol. XVI, Part II, 1916, pp. 320–342. Title clearly indicates the material covered.

Nusbaumer, M.

"Étude Comparative sur les Essais au Choc Simple, les Essais aux Chocs Répétés, les Essais de Flexion Rotative et les Essais de Flexion Alternee," *Rev. Met.*, Vol. 11, 1914, pp. 1133–1189. This comparison of impact and fatigue tests includes a historical outline, the influence of chemical composition, of heat treatment, form of specimen, velocity of striker, etc. The apparatus and material used are described and the results of the tests given with conclusions.

Olsen, T. Y.

"New Types of Impact Testing Machines for Determining Fragility of Metals," *Proc.*, Am. Soc. Test. Mats., Vol. XI, 1911, pp. 815–818. Describes a pendulum type of impact machine.

Ono, A.

"Impact Testing Disadvantages," "Miscellaneous Notes on Impact Tests," Memoirs of the College of Eng., Kyusher Imperial University, Vol. 2, No. 1, 1920, pp. 82–116. Disadvantages found to be of slight importance.

Page, L. W.

"A New Impact Machine," *Proc.*, Am. Soc. Test. Mats., Vol. VII, 1907, pp. 601–606. A drop testing machine designed for testing the toughness of rock. It is intended to measure the degree to which a rock possesses the property of standing up under traffic. It may also be used for ascertaining the detonation energy required for a number of explosives.

"Relation Between the Tests for the Wearing Qualities of Road-Building Rocks," *Proc.*, Am. Soc. Test. Mats., Vol. XIII, 1913, pp. 983–995. Describes a drop test machine for determining the toughness of rock and shows the relation between toughness and hardness. Results of tests on typical road-building rocks are given.

Palmer.

See Fereday, F. J.

Perot, A.

"Sur les Efforts Developpes dans le Choc d'Eprouvettes Entaillees," *Comptes Rendus*, Vol. 137, 1903, pp. 1044–1046. Description of a photographic method of obtaining a curve of the behavior of an impact specimen under test.

Perot, A., and Levy, H.

"Sur la Fragilite des Metaux," *Comptes Rendus*, Vol. 138, 1904, pp. 474–476. Curves obtained photographically showing the behavior under impact of two metals for which the tensile test results are given.

"Sur la Fragilite de Certain Aciers," *Comptes Rendus*, Vol. 139, 1904, pp. 1198–1200. Description of improvements in photographic apparatus for impact tests.

Philpot, H. P.

"Some Experiments on Notched Bars," *Proc.*, Inst. Automobile Engr., Vol. 12, April, 1918, pp. 235–370. Describes the results of experiments to obtain a round specimen which would give the same results as the standard square specimen. Many tests were made in the Charpy and the Izod impact machines and under static load. Much of the material was heat treated, sometimes incorrectly by intent. Conclusions: (1) The dimensions for a round specimen are given which gives practically the same test results as the square one, (2) specimens with notches having relatively large radii at the root are unsatisfactory, (3) tensile tests even if an extensometer is used do not show material having low impact value, (5) Charpy and Izod pendulum machines give similar results.

Pilcher, J. A.

"Impact and Its Relation to Damage Claims," *Ry. Age*, Vol. 71, July 9, 1921, pp. 77–79.

Plank, R.

"Betrachtungen Über Dynamische Zugbeanspruchung," *Zeit.*, Ver. Deut. Ing., Vol. 56, Jan. 6, 1912, pp. 17–24. Theoretical discussion of the deformation of materials under tensile impact stresses. Description of apparatus for making tests and curves showing the relation of space, velocity and force.

Preuss, E.

"Versuche Über die Spannungsverteilung in Gekerbten Zugstaben," *Zeit.*, Ver. Deut. Ing., Vol. 57, April 26, 1913, pp. 664–667. Experiments showing the great stress at the bottom of the notch in notched tensile specimens under static load.

"Kerbwirkung bei Dauerschlagbeanspruchung," *Zeit*, Ver. Deut. Ing., Vol. 58, May 2, 1914, pp. 701–703. The results of repeated impact tests of soft steel notched bars showing the effect of notches in lowering the impact resistance especially if the notches have sharp reëntrant angles.

"Die Festigkeit von Schweisseisen gegenüber Stossbeanspruchung," *Stahl und Eisen*, Vol. 34, July 16, 1914, pp. 1207–1209. Discussion with some results of impact and other tests of wrought iron.

Primrose, H. S., and Glen, J. S.

"Impact Testing Machine," *The Engineer*, Vol. 125, May 17, 1918, p. 435. Description and photograph of Amsler impact machine.

Revillon, L.

See also Guillet, L.

"La Definition de la Resilience et les Essais au Choc," *Rev. Met.*, Vol. 5, 1908, pp. 887–892. An investigation of the effect of variables in the shape of the specimen upon the test results.

"The Definition of Resilience in Impact Tests," Int. Assoc. Test. Mats., III–3, V Cong., Copenhagen, 1909, pp. 1–5. Results of impact tests on notched steel specimens with recommendations for comparing the results of tests on specimens of different sizes.

Ridsdale, C. H.

"Brittleness in Soft Steel," *Jour.*, Iron and Steel Inst., Vol. 53, Part 1, 1898, pp. 220–234. Results of tests on soft steel, including impact tests. Specimens were placed on a span of 3 ft. and a ball weighing 1000 lb. dropped on middle. The specimens were reversed after each blow.

Richardson, C., and Forrest, C. N.

"Impact Tests of Asphalt Paving Mixtures," *Proc.*, Am. Soc. Test. Mats., Vol. V, 1905, pp. 381–387. Describes the application of the Page impact machine for rock to asphalt paving mixtures. Also gives the results of tests on a number of asphalts.

Robin, F.

"Nouvel Appareil pour l'Essai de Choc sur Barreaux Entaillées au Lisses les Essais de Poinconnage et de Cesaillement," *Technique Moderne*, Vol. 2, Jan., 1910, pp. 112–116. Description of fixtures for holding notched impact specimens.

Rogers, F.

"The Behavior of Steel under Combined Static Stress and Shock," *Mech. Engr.*, Vol. 26, Nov. 11, 1910, p. 617; *Jour.*, West of Scotland Iron and Steel Inst., Nov., 1912. Abstract of a paper read at Physical Society of London. The time rate of increase of stress is important. Experiments made by applying impact stresses to steel under static loading. The machine having novel features was exhibited and described. Steel was found to be less resistant to shock while under static stress.

Roman, C. V.

"On Some Applications of Hertz's Theory of Impact," *Physical Rev.*, Vol. 15, April, 1920, pp. 277–284. Discusses problem of transverse impact of a solid sphere on an infinitely extended elastic plate of finite thickness, and attempts to calculate theoretical coefficient of restitution which is a function of elastic constants and densities of materials, diameter of sphere, and thickness of plate and velocity of impact. Calculation results in simple formula for coefficient of restitution.

Rosenhain, W.

"Deformation and Fracture in Iron and Steel," *Jour.*, Iron and Steel Inst., 1906, Part 2, pp. 189–228. A study of slip bands and the fractures of iron and steel from tensile shock tests. Wrought iron and mild steel were used. Many photomicrographs are given.

Introduction to Physical Metallurgy, Constable and Co., London, 1914, pp. 232–240. Discussion of impact testing and its value particularly with respect to the notched bar impact test.

"The Engineering Relations of Shock and Fatigue," *Automotive Industries*, June 10, 1920, p. 1293.

Rudeloff, M.

"Prüfung von Eisen und Stahl an Eingekerbten Stücken," *Stahl und Eisen*, Vol. 22, Part 1, April 1, 1902, pp. 374–380; April 15, 1902, pp. 425–432. Discussion of investigation of impact tests of notched specimens of iron and steel. Mention is made of the work of Reiser, Tunner, Stockl, Dudley, Mehrtens, Krohn, Kerpely, Sorby, Charpy, Considere, Barba, Steiner, Vavra, Rudeloff, Bach, Tetmajer, Martens, Ast, Brinell, LeChatelier, Fremont, Vanderheym, Russel. The effect of temperature, appearance of fracture, shape and size of specimen, speed of tup, are considered, as well as the relation of static to impact test results.

Russell, S. B.

"Experiments with a New Machine for Testing Materials by Impact," *Trans.*, Am. Soc. Civ. Engr., Vol. 39, June, 1898, pp. 237–272. Describes a pendulum machine of his own design and the results of 700 tests. Results on rough and machined cast-iron bars and on brick are given. Notches were used for cast iron, wood, bronze, aluminum, iron, as well as for soft, medium, plow and cast steels. Discussion of the theory and the errors which occur in impact testing. Conclusions: (1) For brittle materials definite values for resilience may be obtained, (2) For tough materials definite values may be obtained if standard specimen is used. The resilience of cast iron is greatly increased by planing off the surface. Metals show a higher ultimate resilience under impact than under gradually applied loads.

"Impact Tests of Structural Steel," *Trans.*, Am. Soc. Civ. Engr., Vol. 43, June, 1900, pp. 1–19. Describes a modification of his pendulum impact machine used for beam specimen by which tensile specimens can be tested. The errors due to the inertia and to the spring in the bar struck by the pendulum which loads the specimen are discussed. The tensile impact resistance of rolled steel can not be predicted from the tensile strength and elongation. These tests should be valuable in judging the quality of structural steel.

Sankey, H. R.

See also Blount, B.

"Impact Testing," *The Engineer*, Vol. 101, Jan. 26, 1906, pp. 84–86. Description of machines and specimens with results of tensile and impact tests on various materials, mostly steel.

Sankey, H. R., and Smith, J. K.

"Heat Treatment Experiments with Chrome-Vanadium Steel," *Proc.*, Inst. Mech. Engr., 1904, Part 4, pp. 1235–1317. The impact tests are described on p. 1242 and discussed on p. 1251. The results of impact tests are given with those from tensile and Arnold (fatigue) tests.

Alloys Research, Inst. Mech. Engr., Feb., 1907, pp. 281–287. Description of cold bend machine from which a diagram was obtained, with comparison of results with fatigue and impact tests on steel.

Schmid, A.

"On the Influence of the Shape of the Bar and of the Treatment of the Metal upon the Results of Notched Bar Impact Tests," Int. Assoc. Test. Mats., IV–6, VI Cong., New York, 1912, pp. 1–5; *Rev. Met.*, Vol. 9, 1912, pp. 1182–1183. Recommendations as to size of specimen and method of preparation based on experiments.

"On the Influence of the Shape of the Bar and of the Treatment of the Metal upon the Results of Notched Bar Impact Tests," Am. Foundrymen's Assoc., Vol. 21, 1913, pp. 479–483. The results of impact tests of two grades of mild Siemens-Martin steel are given. The material was either "shaped cold," "forged" to size, pressed warm or hard drawn.

"Vergleichende Versuche mit dem Amsler-Laffonschen Fallwerk und einem Neuen Kleinen Pendelhammer von 25 kgm. Arbeits Inhalt von Mohr und Federhaff in Mannheim," *Zeit.*, Ver. deut. Ing., Vol. 59, May 22, 1915, pp. 423–426. A comparison of the results obtained on a vertical drop and a pendulum impact machine with a discussion of the errors which may occur.

Schule, F., and Brummer, E.

"On Notched Bar Impact Bending Tests," Int. Assoc. Test. Mats., III–2, V Cong., Copenhagen, 1909, pp. 1–6. Description of drop test machine and some results of tests. The conclusion is reached that if the volume stressed beyond the yield point (polished specimen) is used in computing the work per unit volume the influence of depth of notch can be eliminated and the effect of shape of notch determined.

Schulz, E., and Fiedler, R.

"On the Sensibility of Zinc to Notches," *Forschungsarb.*, Geb. Ingenieurw., Sonderreihe M., Vol. 1, 1919, p. 29.

Seaton, A. E., and Jude, A.

"Impact Tests on the Wrought Steels of Commerce," Inst. Mech. Engr., Vol. 4, Nov., 1904, pp. 1135–1230. Description of a drop impact machine and the results on notched steel specimens with discussion of the relation of impact tests to service of the material and the way in which failure occurs, illustrated by micrographs.

Seehase, H.

"Die Experimentalle Ermittlung des Verlaufes der Stosskraft und die Bestimmung der Deformationsarbeit beim Stauchversuch," *Zeit.*, Ver. Deut. Ing., Vol. 38, Aug. 22, 1914, pp. 1345–1348. Description of a vertical drop impact machine and photographic apparatus for obtaining a space-time diagram. The variation in force and the work of deforming the specimen may be found. Tests of copper, brass, steel and rivet iron show that these materials behave differently under impact than under static loading.

Simonot, E.

"Methods Employed in Testing Metals," *Bul.*, Soc. Industrie Minerale, Vol. 6, pp. 115–166.

Smith, C. A. M.

"Methods of Impact Testing," *Cassier's Mag.*, Vol. 40, June, 1911, pp. 155–162. General description of impact testing machines, specimens, and methods of making the tests.

Smith, E. B.

"Measurement of Impact," *Proc.*, Am. Soc. Test. Mats., Vol. 21, 1921, pp. 1073–1085. Describes a method for measuring the force of impact of motor trucks on highways. Two methods are described, the autographic and deformation. The autographic method involves the use of a space-time curve autographically drawn at the instant of impact. The deformation method involves the measurement of deformation of a copper cylinder.

Smith, J. K.

See Sankey, H. R.

Snyders, J., and Hackstroh, P.

"Drop Tests on Nicked Bars," *Zeit.*, Oesterreichische Ing. und Arch. Ver., Dec. 22, 1905.

Southwell, R. V.

"Note on the Application of Dimensional Theory to Notched-Bar Impact Tests," Aeronautical Research Com. (Eng. Reports, etc., No. 732, M. 2), Jan. 1921, pp. 1–8. The application of a dimensional theory to impact testing shows that the energy should be a function not only of the striking velocity for brittle materials but of the velocity and the dimensions of the specimen, if the stress at rupture depends in addition upon the rate of straining as in ductile materials. Investigational work is needed. It seems probable that much of the energy measured is propagated through the pendulum arm into other parts of the apparatus and is lost by dissipation. Apparatus having both anvil and striker suspended by cords so as to swing freely, is suggested as suitable for research work and also for routine testing.

Stagg, H. J., Jr.

"Impact Tests of Steel," *Iron Age*, Vol. 99, April 5, 1917, p. 839; *Blast Furnace and Steel Plant*, May, 1917. Abstract of paper, "Impact Tests, Their Relation to Brinell, Tension and Torsion Tests," before Steel Treating Research Club of Detroit. Describes experiments on chrome-vanadium and nickel-chrome steel. Discussion by Sir R. A. Hadfield in *Iron Age*, Vol. 99, May 17, 1917, p. 1192. Emphasizes need for impact test. Prefers Fremont machine.

Stanton, T. E.

"Repeated Impact Testing Machine at the National Physical Laboratory," *Collected Researches*, Nat. Physical Lab., Vol. 6, 1910, pp. 2–6; *Engineering*, July 13, 1906, pp. 33–34. Description of a vertical drop repeated impact testing machine.

Stanton, T. E., and Bairstow, L.

"The Resistance of Materials to Impact," *Collected Researches*, Nat. Physical Lab., Vol. 6, 1910, pp. 9–31; *Proc.*, Inst. Mech. Engr., Nov., 1908. An investigation of iron and steel under single blow and repeated blow impact tests with results.

Stanton, T. E., and Batson, R.

"The Characteristics of Notched Bar Impact Tests," *Proc.*, Inst. Civ. Engr., Dec., 1920. Experiments were made upon specimens of similar shape but of different dimensions in apparatus specially constructed for the purpose of maintaining geometrical similarity. The results showed that even under these conditions there is considerable "scale effect" in some materials, that is, the work expended in fracture per unit volume of material is often dependent upon the absolute dimensions of the specimen.

Stoughton, B.

See Macgregor, J. S.

Stribeck, R.

"Die Kerbschlagprobe und das Aehnlichkeitsgesetz," *Zeit.*, Ver. Duet. Ing., Vol. 59, Jan. 16, 1915, pp. 57–60; *Stahl und Eisen*, Vol. 35, April 15, 1915, pp. 392–396. Discussion of the law of similarity as applied to impact tests and the results of impact tests on several materials.

Thallner, O.

"Über Materialeigenschaften im Zerreis-, Kerbreiss- und Kerbschlagversuch," *Stahl und Eisen*, Vol. 28, July 29, 1908, pp. 1081–1088; Aug. 12, 1908, pp. 1167–1174; Aug. 19, 1908, pp. 1209–1215. A discussion of the tensile properties of metals with the results of tensile and impact tests on plain and notched bars of wrought iron, carbon and chrome nickel-steel. The shape of the notches was varied. Many stress diagrams are shown.

Thomas, J. J.

"The Charpy Impact Test on Heat-Treated Steels," *Proc.*, Am. Soc. Test. Mats., Vol. XV, Part II, 1915, pp. 62–79; *Mech. Engr.*, Vol. 36, Aug. 6, 1915, pp. 107–108. Describes the Charpy impact machine and gives in detail four experiments made with it, the first upon heat-treated steel, the second on nickel-vanadium steel, the third upon low-carbon steel quenched and drawn at various temperatures, and the fourth demonstrating the effect of the shape of notch on the Charpy bar. Test results are included for each of these experiments.

Thompson, F. C.

"The Impact Testing of Metals," *Sci. Am. Monthly*, Vol. 1, Feb. 1, 1920, p. 138. A good summary on impact testing, particularly on notched bar specimens.

Thurston, R. H.

"On the Mechanical Properties of Materials of Construction," *Trans.*, Am. Soc. Civ. Engr., Vol. 3, 1874, pp. 1–30; Vol. 4, 1875, pp. 265–276; Vol. 5, 1876, p. 102. A description of experiments on steels, cast iron, copper, bronze, etc., under static tensile and torsional loads. Autographic stress diagrams were obtained and conclusions drawn regarding the effect of time, temperature, overstrain, etc., upon the properties of the material.

Tiemann, H. D.

"The Theory of Impact and Its Application to Testing Materials," *Jour.*, Franklin Inst., Vol. 168, Oct., 1909, pp. 235–259; Nov., 1909, pp. 336–364. Theoretical discussion of impact on transverse, tensile and compression members.

Tredgold, T.

"Strength of Cast Iron," printed for J. Taylor, London, 1824, pp. 245–268. Theoretical discussion of the strength of cast iron to resist an impulsive force.

Tschudi, E. U.

"Duration of Impact Bars," *Phys. Rev.*, Vol. 19, Dec., 1921, pp. 423–430.

Turner, W. P.

See Hatt, W. K.

Unwin, W. C.

"Notched Bar Tests," *Engineering*, Vol. 108, Sept. 12, 1919, pp. 329–330. Discussion of results which have been reported by Charpy and Thenard and in British Assoc. Report for 1918. The mean error, variation of results of tests on a given material with a given sized test bar, work of rupture is not proportional to the size of the bar, empirical formula of reduction for notched bar tests, are some of the subjects considered.

Waltenberg, R. G.

"Note on Notched Bar Impact Tests and Toughness of Monel Metal," *Chem. and Met. Eng.*, Vol. 25, Aug. 24, 1921, pp. 322–323; Nov. 2, 1921, pp. 816–821 (discussion by Comstock). Results of tests, tensile, Charpy and Izod impact with Brinell and scleroscope hardness, of hot-rolled monel-metal rods 1 in. and $\frac{3}{4}$ in. in diameter and a comparison of these with other metals.

Waterbury, L. A.

"*Laboratory Manual*," Wiley and Sons, New York, 1912, "Impact Test of Iron or Steel," pp. 121–123, "Impact Test of Wood," p. 134.

Wawrziniok, O.

Handbuch des Materialprüfungswesen, Julius Springer, *Berlin*, 1908, VII, "Versuche mit Stossweiser Beanspruchung; Die Schlagfestigkeit," p. 107; "Der Schlagzerreissversuch," p. 108; "Der Stauchversuch," pp. 108–111; "Der Schlagbiegeversuch," p. 111; "Versuche mit dem Fallwerke, Konstruktions grundsätze der Fallwerk," pp. 111–113; "Kontrolle der Fallwerke," p. 113; "Ausführung eines Schlagbiegeversuchen," pp. 113–114; "Beispiel von Lieferungsvorschriften fur Schienen," pp. 114–115; "Versuche mit dem Pendelhammer (Kerbschlagbiegeprobe), Konstruktionsgrundsätze für Pendelhammer und Allgemeines," pp. 115–119; "Ausführung einer Kerbschlagbiegeprobe," pp. 120–121; "Einfluss der Form und der Temperatur des Probestabes auf das Versuchsergebens," pp. 121–122. Description of drop and pendulum impact testing machines and apparatus with a detailed statement of methods of making the tests and a statement of influence of the form of specimen and its temperature on the test results.

Welikhow, P.

"Note on the Rupture of Normal Cylindrical Test Samples by Longitudinal Impact," Int. Assoc. Test. Mats., III–8, V Cong., Copenhagen, 1909, pp. 1–9. Description of drop tensile impact machine and the results of tests of steel.

West, T. D.

Metallurgy of Cast Iron, Cleveland Printing and Publishing Co., Cleveland, Ohio, 1902, "Impact or Shock Tests of Iron," pp. 439–442. The value of impact tests of cast iron is discussed and Outerbridge's experiments demonstrating that the strength is increased by repeated light blows are described.

Willis, F. W.

See Edwards, A. C.

Wilson, T. R. C.

See Newlin, J. A.

Wilson, A. B.

The Foundry, Vol. 48, Aug. 1, 1920, pp. 616–617. Results of impact, tensile, compression and hardness tests on seven bronzes. A brief description of the Fremont, McAdam, and Landgraf Turner machines is given.

SUBJECT INDEX TO BIBLIOGRAPHY ON IMPACT TESTING.

For references on a subject, refer to the subject in this index, then to the authors listed there.

General.

Charpy, Elliott, Fereday, Hadfield, Hatfield, Hatt and Marburg, Howe, Johnson, Leber, Leon and Ludwik, Martens, Martens and Heyn, Martens and Hinrichsen, Memmler, Merriman, Nusbaumer, Rosenhain, Rudeloff, Russell, Smith, C. A., Thompson, Wawrziniok.

Theory.

Akimoff, Anonymous 29, 30, Auspach, Bovey, Breuil, Carpenter, Charpy, Davidenkoff, Elmendorf, Fuller, Grent, Johnson, Kreuger, Lanza, Leitzmann, Martens and Heyn, Merriman, Mimey, Plank, Roman, Southwell, Stribeck, Thurston, Tiemann, Tredgold.

Methods of Testing.

Anonymous 15, 18, 23, 26, 28, Blount, Breuil, Charpy, Colby, Derihon, Dix, Goss, Guillery, Harboard, Hatt and Marburg, Jackson, Johnson, Keep, Kuhlman, Lanza, Macgregor and Stoughton, Martens, Martens and Heyn, Memmler, Nusbaumer, Ono, Page, Richardson, Rogers, Rudeloff, Schmid, Smith, E. B., Unwin, Waterbury, Wawrziniok.

Impact Machines.

(*a*) General:

Anonymous 3, 6, 9, 12, 20, 24, 33, Breuil, Carpenter, Charpy, Dunn, Edwards, Endsley, Fereday and Palmer, Fremont, Honiger, Johnson, Kreuger, Magruder, Margerum, Martens, Mattimore, Memmler, Nusbaumer, Perot, Perot and Levy, Plank, Robin, Rogers, Rudeloff, Russell, Sankey, Schmid, Smith, E. B., Wawrziniok, Wilson.

(*b*) Types of Machine:

Amsler.—Primrose and Glen.
Arnold.—Arnold, McWilliams and Barnes.
Avery.—Anonymous 1.
Charpy.—Anonymous 2, 13, Charpy, Dix, Langenberg, Philpot, Thomas.
Drop.—Anonymous 14, 16, 21, 27, Blount, Davidenkoff, Dunn, Gagarine, Gooch, Goss, Holt, Jungst, Keep, Langenberg, McGarvey, MacLachlan, Martin, Page, Schule and Brummer, Seaton and Jude, Seehase, Welikhow.
Eden-Foster.—Anonymous 5.
Estrada.—Anonymous 27.
Fremont.—Anonymous 28, Derihon, Fremont, Hall, Harboard.
Guillery.—Anonymous 17, Guillery, Guillet, Martens and Heyn.
Hatt-Turner.—Elmendorf, Hatt, Hatt and Turner.
Izod.—Dix, Harboard, Izod, Philpot.
McAdam.—McAdam.
Olsen.—Dix, Olsen.
Pendulum.—Ehrensberger, Jungst, Keep, Martens and Heyn.
Stanton.—Anonymous 11, Ensaw, Gibson, Stanton, Stanton and Bairstow.

(*c*) Effect of Speed:

Anonymous 6, 9, Bauman, Breuil, Charpy, Charpy and Cornu-Thenard, Gessner, Hadfield and Main, Hatt, LeChatelier, Martens, Martens and Heyn, Nusbaumer, Philpot, Rudeloff, Seehase.

Specimens.

(*a*) General:

Anonymous 19, 30, Breuil, Coker, Harboard, Johnson, Langenberg, Martens, Rudeloff, Seehase, Thompson, Wawrziniok.

(*b*) Effect of Size and Shape, including Notch:

Anonymous 6, 21, Bauman, Breuil, Charpy, Charpy and Cornu-Thenard, Ehrensberger, Fremont, Gessner, Heyn, Howe, Leon and Ludwik, Martens and Heyn, Nusbaumer, Philpot, Preuss, Revillon, Rudeloff, Russell, Schmid, Stanton and Batson, Thallner, Thomas, Unwin, Wawrziniok.

(*c*) Effect of Temperature:

Anonymous 6, Charpy, Denis, Ehrensberger, Guillet, Johnson, LeChatelier, Rudeloff, Wawrziniok.

(*d*) Fractures:

Brearley, Freminville, Rosenhain, Rudeloff, Seaton and Jude.

Materials.

Aluminum.—Dix, Gibson, Russell.

Asphalt Paving.—Richardson.

Brass and Bronze.—Izod, Russell, Wilson.

Concrete.—Mattimore.

Copper.—Bancke, Guillet, Hatt and Turner.

Fire Brick.—Anonymous 16.

Iron.—Andrews, Anonymous 6, 9, 27, Bauman, McAdam, Preuss, Russell.

Iron, Cast.—Brechbuhl, Gessner, Johnson, Jungst, Russell.

Lead.—Hatt and Turner.

Monel Metal.—McAdam, Waltenberg.

Rock.—Anonymous 25, Jackson, Page.

Steel.—Anonymous 6, 27, Berndt, Blount, Denis, Ehrensberger, Gessner, Greaves, Guillet, Hall, Harboard, Holt, Izod, Johnson, Langenberg, Leon and Ludwik, Longmuir, McAdam, Milton, Philpot, Ridsdale, Russell, Sankey and Smith, Sankey, Schmid, Seaton and Jude, Stagg, Stanton and Bairstow, Thallner, Thomas.

Wood.—Elmendorf, Hatt and Turner, Russell.

Zinc.—Schulz and Fiedler.

Impact Testing of Shipping Containers.

Anonymous 22, Newlin and Wilson.

Impact Testing of Rails.

Anonymous 4, Dudley, Martin.

Impact Testing of Railroad Equipment.

Goss, Hatt and Marburg.

Impact Testing of Track.

Anonymous 33.

Value of Impact Tests.

Charpy, Derihon, Greaves, Hadfield, Harboard, Howe, Hubert, Langenberg, Leber, Martens and Heyn, Mattimore, Merriman, Nusbaumer, Ono, Perot and Levy, Philpot, Rosenhain, Rudeloff, Russell, Schmid, Seaton and Jude, Stagg, Stanton and Bairstow, Thomas, Thompson, Wawrziniok, West.

CHRONOLOGICAL INDEX TO BIBLIOGRAPHY ON IMPACT TESTING

Refer to the year in this index, then to the authors listed there.

1824.—Tredgold.
1874.—Thurston.
1881.—Anonymous 9.
1885.—Lanza.
1891.—Andrews.
1893.—Bovey.
1894.—Anonymous 27, Merriman.
1897.—Dunn, Johnson, Merriman
1898.—Ridsdale, Russell.
1899.—Hatt and Marburg, Keep, Martens.
1900.—Colby, Leitzmann, Magruder, Russell.
1901.—Anonymous 31, Fremont, Hatt.
1902.—Anonymous 4, 23, 31, Hatt and Marburg, Rudeloff, West.
1903.—Anonymous 29, Goss, Izod, Perot.
1904.—Anonymous 6, Arnold, Breuil, Charpy, Guillery, Hatt, Perot and Levy, Sankey and Smith, Seaton and Jude.
1905.—Anonymous 1, 25, Dick, Milton, Richardson, Snyders and Hackstroh, Thomas.
1906.—Anonymous 17, Hadfield, Hatt and Turner, Lanza, Rosenhain, Sankey.
1907.—Anonymous 15, Dilber, Ehrensberger, Freminville, Gessner, Leber, Memmler, Page, Sankey.
1908.—Anonymous 26, Harboard, McGarvey, Martin, Revillon, Thallner Wawrziniok.
1909.—Breuil, Charpy, Dunn, Giesen, Grent, Guillet and Revillon, LeChatelier, Leon and Ludwik, McWilliams and Barnes, Revillon, Schule and Brummer, Tiemann, Welikhow.
1910.—Anonymous 2, 7, 11, 13, Blount, Breuil, Dudley, Gessner, Leon and Ludwik, MacLachlan, Robin, Rogers, Stanton, Stanton and Bairstow.
1911.—Auspach, Longmuir, Macgregor and Stoughton, Olsen, Smith.
1912.—Anonymous 14, 21, 28, Bancke, Bauman, Brechbuhl, Charpy, Davidenkoff, Derihon, Fremont, Gagarine, Gessner, Honiger, Martens and Heyn, Martens and Hinrichsen, Plank, Schmid, Waterbury.
1913.—Carpenter, Charpy and Cornu-Thenard, Fuller and Johnston, Hall, Hubert, Jungst, Mimey, Page, Preuss, Schmid.
1914.—Charpy, Charpy and Cornu, Denis, Nusbaumer, Preuss, Rosenhain, Seehase.
1915.—Anonymous 18, 30, Elliott, Endsley, Gessner, Schmid, Stribeck.
1916.—Anonymous 16, 22, Elmendorf, McAdam, Mimey, Newlin and Wilson.
1917.—Anonymous 33, Brearley, Charpy, Charpy and Cornu-Thenard, Ensaw, Howe, Jackson, Stagg.
1918.—Anonymous 26, Berndt, Charpy, Edwards, Gooch, Johnson, Mattimore, Philpot, Primrose and Glen.
1919.—Akimoff, Anonymous 3, 5, Cornu-Thenard, Dix, Freminville, Greaves, Hatfield, Schulz and Fiedler, Unwin.

1920.—Anonymous 8, 19, 24, Dix, Gibson, Greaves and Moore, Hadfield and Main, Jones and Greaves, Langenberg, Morean, Ono, Roman, Rosenhain, Stanton and Batson, Thompson, Wilson.

1921.—Anonymous 10, 12, 20, Coker, Fereday, Fereday and Palmer, Guillet, Kreuger, Langenberg, Legrand, Margerum, Pilcher, Smith, Southwell, Tschudi, Waltenberg.

1922.—Kuhlmann.

IMPACT TESTS OF METALS.[1]

BY D. J. McADAM, JR.[2]

In investigation of the behavior of metals under gradual application of load, attention is usually centered on measurement of stresses and strains. The total energy required for fracture, while it may be calculated, is usually of minor importance. In investigation of the behavior of metals under impact, however, the measurements of stresses and their relations to strains are not so easily made. For this reason, although some impact testing machines are adapted for determination of stresses under impact, most machines are adapted only for measurement of the total energy required for fracture. Investigators, moreover, have directed their attention almost exclusively to measurement of the latter quantity. In discussion of impact testing machines and specimens, therefore, attention will be centered first on the measurement of the total energy required to break the specimen.

The essential parts of an impact testing machine are: (1) A moving mass, known as a hammer, knife or tup, of known kinetic energy, which should be great enough to cause fracture of a test specimen placed in its path; (2) an anvil on which the test specimen is placed to receive the blow of the moving mass; and (3) a device for measuring the residual kinetic energy in the moving mass after the specimen has been fractured.

Impact testing machines may be divided into three types according to the general methods of obtaining the necessary kinetic energy in the moving mass: (1) Drop weight machines, in which the kinetic energy of the tup is obtained by free fall under the action of gravity; (2) pendulum machines, in which the tup is a pendulum which, after swinging through a definite angle to the bottom of its path, strikes a specimen placed opposite the center of percussion; and (3) flywheel machines, in which the knife is attached to a flywheel whose kinetic energy before and after impact can be measured.

While there is only one well-known machine of the third type, there are a number of machines of the first two typct. Machines of either of the first two types vary greatly in capacity and details of construction. The only essential distinction between the machines of any one type, however, is in regard to the type of specimen that the machine is designed to break.

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[1] Printed by permission of the Secretary of the Navy.

[2] Metallurgist, U. S. Naval Engineering Experiment Station, Annapolis, Md.

Though there are many varieties of impact specimens, they may all be classified under a few types: (1) Tension, (2) Shear, (3) Simple beam, and (4) Cantilever. Specimens of any type may be either notched or unnotched. Types of specimens and the most important individual specimens will be described and discussed later.

DESCRIPTION OF MACHINES.

It is not considered advisable to devote much space to detailed descriptions of machines. It would seem to be the better plan to describe briefly a few prominent machines, classifying each according to its type, according to the type of specimen that it is designed to break, and according to the method of measuring the residual energy in the hammer or tup.

Drop Weight Machines.—Of the drop-weight type of machine, Fremont has been the most distinguished advocate. The machine that bears his name is perhaps the best known of this type. This machine is adapted for use of either a 10 or 15-kg. hammer. The hammer falls from a height of 4 meters and after breaking the specimen, strikes a platen resting on two calibrated springs. The downward movement of the platen against the resistance of the springs is indicated by a magnifying device which causes a pointer to move over a calibrated scale. The specimen is of the simple beam type.

There is an Olsen tension testing machine of the drop-weight type. It is provided with 250 and 500-lb. hammers with a maximum drop of 7 ft. The available energy is therefore great enough to permit tests of standard threaded tension test specimens of 0.505 in. diameter or short lengths of rod of the same cross-section held by wedge grips. The machine is equipped with a revolving drum on which a curve is drawn by the falling hammer during impact. The speed of the drum is indicated by a parallel graph drawn by an electrically operated tuning fork. It is thus possible to calculate the velocity changes of the hammer, and consequently the stress-strain relations as well as the total energy changes during impact.

The Hatt-Turner impact testing machine, while used principally in testing wood, can also be used in testing metals. It is made in two sizes. The smaller size is provided with 50, 100 and 250-lb. hammers. The larger size has also a 500-lb. hammer. A record of the behavior of the specimen during impact is traced on a revolving drum by means of a pencil attached to the hammer.[1]

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[1] For a more complete description of this machine, see paper by Thomas R. C. Wilson, p. 55.—ED.

Pendulum Impact Machines.—The Charpy machine is the best known of those designed primarily for breaking a specimen of the notched simple beam type. In this machine a "knife" is inserted at the center of percussion of the pendulum so that the edge is in a vertical position at the instant when it strikes the horizontally placed test specimen. The angle between the two converging sides of the knife is 30 deg. and the striking edge is rounded to a definite radius, which in the smaller machine is about 2 mm. The ends of the test specimen are supported by the anvil of the machine and the specimen is adjusted so that the hammer strikes the specimen directly opposite the centrally located notch.

The machine is made in two sizes. The smaller size has a capacity of about 30 kgm. (217 ft-lb.), the larger has a capacity of about 300 kgm. The smaller machine is designed to test a notched simple beam specimen of similar shape to that used in the larger machine but whose dimensions are one third as great. For testing non-ferrous alloys, especially aluminum alloys, an American made Charpy machine is provided with an additional hammer one-tenth the weight of the standard hammer. In addition to notched transverse specimens, the Charpy machine is adapted for testing specimens under impact-tension. For this purpose the back of the pendulum head is tapped and threaded for holding one end of a test piece. On the other threaded end of this test piece a hardened steel block can be placed. When the pendulum drops, this block strikes against prolongations of the anvil and is stopped. Under these conditions the kinetic energy of the pendulum is sufficient to cause fracture of the specimen.

Amsler pendulum machines are designed to test notched or unnotched specimens of simple beam type. These machines are of either 110 or 550 ft-lb. capacity.

The Izod machine is designed for testing a notched specimen of the cantilever type. The striking edge of the hammer is horizontal and is so adjusted as to strike the vertically held specimen at a definite distance above the notch. In recent Izod machines provision is also made for testing specimens under impact tension. There are several well-known machines of the Izod type which differ merely in capacity, in the distance from the notch to the striking edge, and in unessential details of construction.

The pendulum type of machine has also been used for subjecting specimens to impact shear. In the original investigation of this method of testing by the present writer the striking edge of an Olsen machine of the Izod type was lowered so that there was mere clearance between the striking edge and the top of the anvil. A machine has since been built especially for this method of testing. Although the impact-shear test has been used only on unnotched specimens, it might well be tried on notched specimens in investigation of the influence of depth and shape of notch. Drop-weight machines as well as pendulum machines could be used in the impact-shear test.

Flywheel Machines.—In the Guillery machine, the striking edge or knife is attached to a flywheel. The knife is so mounted that it can assume either a sheathed or unsheathed position. The machine is so designed that the velocity of the knife at the instant of impact is equal to that produced by a free fall of 4 meters. The polar moment of inertia of the flywheel is such that at this velocity the available energy is more than sufficient to break the specimen used. For measuring the energy immediately before and after impact, use is made of the principle that the kinetic energy is proportional to the centrifugal force. The tachometer for measuring centrifugal force consists of a small water turbine with vertical water tube in which the height of the water is a measure of the centrifugal force. The tube is so calibrated that the zero of the scale represents the velocity that would be produced by a free fall of 4 meters.

In making a test, the specimen is placed on the anvil and the speed of the flywheel is adjusted until the water in the tachometer tube stands at the zero mark. The unsheathing button is then pressed, and the knife is released and strikes the specimen. The diminution in velocity causes a drop in the height of water in the tachometer tube. The scale reading indicates directly the amount of absorbed energy.

The machine is made in two sizes. The larger size, which has a capacity of 275 kgm. (1989 ft-lb.), is adapted for testing specimens of the large Charpy type. The smaller machine, which has a capacity of 60 kgm. (434 ft-lb.), is adapted for testing the small specimens of the Fremont, Mesnager, or small Charpy type.

Machines for Resilience Measurement under Slow Application of Load.—Although the subject of this symposium is "Impact Testing of Materials," the broader subject of resistance of materials to shock is implied. Since resistance of material to shock is believed to depend on its resilience under slow application of load, it is, therefore, necessary to discuss briefly machines and methods for measurement of this property. While a number of machines with automatic stress-strain recording apparatus are adapted for making resilience measurements on either notched or unnotched bars, a machine has been designed by Humfrey especially for resilience measurements on notched bars subjected to slow bending. The machine measures simultaneously the bending moment and deformation. By integrating, the resilience is obtained. The usefulness of such machines in measurement of resistance to shock will be discussed further below.

Repeated Impact Machines.—While the subject of single impact is large enough for one symposium, it may not be out of place to discuss briefly a few machines for repeated impact. Although there are a number of machines for subjecting material to repeated impact, it seems desirable to limit the discussion to machines in which definitely notched test specimens are used and in which the energy of each blow is determined.

The Stanton machine fulfills these conditions. In this machine, a definitely notched cylindrical specimen is subjected to impact, the specimen being turned through 180 deg. after each blow. One disadvantage of the Stanton machine is that the hammer, after falling from the cam, rebounds from the specimen and strikes several lesser blows before it is again raised by a cam. This defect is overcome in the Matsumura machine by automatic insertion of a metal piece to receive the rebound blows. As in the Stanton machine, the specimen is rotated through 180 deg. after each blow.

Both the Stanton and Matsumura machines are run at very slow speed, not much over 60 blows per minute. The present writer[1] designed a modification of the Stanton machine in which advantage is taken of the rebound of the hammer from the specimen. The hammer is caught at the top of the rebound and lifted to the height for which the cams are set. The speed of the machine is variable and is adjusted to correspond to the natural period of drop and rebound of the hammer. When, therefore, the height of drop is least and the number of blows required for fracture is greatest the speed is also the greatest. The range of speed used in obtaining an impact-endurance test curve extends from about 90 to 600 blows per minute. The specimen is rotated through 90 deg. after each blow.

Stanton states that from the repeated impact test a measure can be obtained of the energy required to break the specimen under single impact. He states that, when the hammer is so adjusted that it breaks the specimen in not more than 100 blows, the total energy of the 100 blows is approximately equal to the energy required to break the specimen under a single blow. As a result of many experiments along this line the author disagrees with Stanton's conclusions. Experiments at the Naval Engineering Experiment Station have shown that the relation between the energy of blow and number of blows endured is, over a considerable range, a simple logarithmic one. This subject will be discussed further in a separate article.

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[1] McAdam, "An Impact-Endurance Testing Machine," *Journal*, Am. Soc. Naval Engrs., Vol. XXIX, No. 4, p. 663 (1917).

RESILIENCE VALUES AS AFFECTED BY TYPE OF MACHINE AND VELOCITY OF HAMMER.

In discussing the total energy required for fracture of a specimen, it is practically necessary to have a single word to represent this value. The term "resilience" has been used for this purpose. This word, since it is derived from a Latin word meaning "to spring back," should not be used to designate work done in deforming a specimen beyond its elastic limit. Nevertheless, since the word has been largely used in this incorrect meaning and since no better word has been suggested, it will be so used in this discussion.

Knowledge in regard to the influence of velocity of hammer on resilience has been in a chaotic condition. There have been and still are widely varying opinions on this subject. The chief difficulty in the way of deciding the question has been uncertainty in regard to the amount of the kinetic energy of the hammer transformed at impact into vibrations of the anvil, frame work of the machine, air, etc. In an article by Captain C. T. Philpot,[1] for example, he gives as the reason for his conclusion that pendulum machines do not give true impact values, the fact that higher resilience values are obtained with notched specimens tested in pendulum machines than are obtained with the same specimens broken by slow bending. He assumes that the greater resilience obtained by impact is due to transformation of part of the kinetic energy into vibrations. According to his assumption, resilience, if correctly measured, should be independent of the speed of deformation of the specimen.

Fremont,[2] however, expresses the opinion that resilience is considerably influenced by the velocity of the hammer at impact. He states that with some steels a variation of the height of drop of hammer between 1 and 4 meters gives variation in the resilience values obtained. Asserting that the minimum velocity should be that produced by a fall of 4 meters, he criticizes the pendulum type of machine because the height of drop is less.

The testing laboratory of the Paris-Lyon-Mediterranee Railway Co. also reached the conclusion that[3] the resilience value is greatly affected by the velocity of the hammer at impact. In publishing results of a number of experiments in which specimens are broken under impact with varying height of drop, they express the conclusion that the true measure of resilience is the value obtained when the specimen is broken under kinetic energy only sufficient to produce fracture. Their results would seem to indicate that with increase in excess energy the resilience increases, but that the increase is not great until the available energy is about double the minimum amount necessary for fracture.

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[1] Philpot, "Some Experiments on Notched Bars," *Journal*, Soc. Automotive Engrs., Dec., 1918, Vol. III, No. 6, p. 347.

[2] Fremont, "The Testing of Metals by Impact on Notched Bars," *Proceedings*, Inter. Assoc. Test. Mats., 6th Congress, New York, First Section, Part IV2 (1912).

[3] "Communication from the Testing Laboratory for Metals of the Paris-Lyon-Mediterranee Railway Co.," *Proceedings*, Inter. Assoc. Test. Mats., 6th Congress, New York, First Section, Part IV5 (1912).

Although Fremont and the laboratory of the Paris-Lyon-Mediterranee Railway Co. do not agree in regard to details, they agree in the conclusion that resilience values are affected by velocity of hammer at impact. The former investigator apparently has the opinion that the effect of variation in height of drop is unimportant at heights above 4 meters. The latter investigators, however, think that variation is unimportant at heights below twice the minimum necessary to cause fracture. Fremont's opinion, therefore, would lead to the conclusion that the pendulum machines, on account of insufficient height of drop, give resilience values that are too low. In the article above referred to, however, he states that pendulum machines have another important defect, which evidently would tend to make the observed resilience values too high. His opinion is that the horizontally moving hammer, since it strikes the anvil at some distance above its base, sets up vibrations which seriously affect the resilience values. The mass of the anvil in the horizontal plane of impact, according to his criticism, is insufficient. He specifies as the minimum essential weight of anvil, forty times the weight of the hammer.

To settle the questions that had been raised in regard to influence of velocity of hammer, mass of anvil, and other differences in the construction of the several types of impact testing machines, Charpy and Cornu-Thenard[1] made an elaborate series of experiments on material of unusual uniformity. In these experiments, they compared the results obtained on impact machines of all three types. To determine the effect of mass, they compared the results obtained with similar specimens on pendulum machines, the masses of whose frame work and anvils were in the ratio of nearly ten to one. They also varied the height of drop of hammer from 0.71 meter to 6.45 meters and compared the results obtained. These various factors include all the variations encountered in the use of impact machines in general use. The results of their investigation may be summed up by saying that within the limits of the investigation the resilience values were found to be uninfluenced by the type of machine used, the weight of hammer and anvil, and the velocity of the hammer at impact. The mass of evidence presented in their report of the investigation is so great and of such uniform significance that it seems to settle conclusively the controversy in regard to this subject.

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[1] Charpy and Cornu-Thenard, "New Experiments on Shock Tests and on the Determination of Resilience," *Journal*, Iron and Steel Institute, Vol. XCVI, No. 11, p. 61 (1917).

In the article referred to, Charpy gives also a brief theoretical discussion of the influence of velocity of hammer on resilience. He refers to experiments by Sarrau and Vielle on measurement of explosion pressures. Their experiments showed that the deformation of cylinders under the same explosion pressure remained practically identical when the times of increase from zero to full pressure varied from 0.0003 to 0.1 second. Charpy in a previous investigation showed, moreover, that in order that the deformations should be influenced appreciably, the rate of application of load must vary from 1 second to 2 or 3 minutes. Since in ordinary impact tests the duration of deformation varies only from about 0.0015 to 0.006 second, they fall within the time limits of the experiments of Messrs. Sarrau and Vielle. Evidently, therefore, within the limits used in ordinary impact tests the striking velocity has practically no influence on resilience measurements.

Resilience measurements are comparable, therefore, when made on similar specimens by means of any of the impact machines in common use. The consensus of authoritative opinion, however, seems to be that with some materials at least, the results of tests would be affected if the striking velocity were outside the range of velocities, 3.4 to 11.25 meters per second, used by Charpy and Cornu-Thenard in their experiments. The British Engineering Standards Association in their "Report on British Standard Forms of Notched Bar Test Pieces" give the striking velocities of some well-known machines as follows: Charpy, 5.3; Izod, 3.5; Fremont, 8.85; Amsler, 4.95; and Guillery, 8.85 meters per second. The report says also: "The results in some materials depend on the striking velocity which should not in any case be less than 3 meters per second. . . . Various machines are in use for making notched bar tests. It does not appear that the results are materially different when tests are made with the standard types of test pieces in these different machines, provided they are properly constructed, calibrated and used, and that the striking velocity is not substantially different."

It is necessary now to consider how resilience values obtained with ordinary impact testing machines compare with the values obtained by use of the Humfrey or any other static machine. In regard to this question the supply of available data is meager. Blount, Kirkaldy and Sankey[1] made a series of comparative tests on similar specimens by static tension and impact tension. They used a specially constructed machine with a 40-ft. drop, a tup weighing 20 lb. and an anvil weighing 2000 lb. Similar unnotched tension specimens 3.8 in. in diameter were tested on this machine and on a static tension machine. The tests included thirteen carbon steels of carbon percentage varying from 0.15 to 0.74 and a chrome-nickel steel. From the results of these tests, the ratios of impact resilience to static resilience were calculated. The ratios vary from 1.31 to 1.75, the average being 1.58 with a mean departure of 0.08.

At the U. S. Naval Engineering Experiment Station some experiments have been made on the ratio between impact resilience and static resilience of notched specimens. Cylindrical specimens 0.5 in. in diameter were used. The diameter at the bottom of the mid-length notch was 0.4 in. and the radius of the notch at the bottom was $\frac{1}{16}$ in. Carbon steels with carbon percentage varying from 0.1 to 0.7 and many alloy steels were thus tested. The ratios of impact resilience to static resilience varied from 1.03 to 1.72, the average being 1.36 with a mean departure of 0.232. This ratio is somewhat smaller than the ratio obtained by Blount, Kirkaldy and Sankey with unnotched specimens. It is probable that the ratio varies with the type of specimen. Experiments are now being made on specimens with notches of various depths and radii.

The available data, therefore, would indicate that impact resilience is in general greater than static resilience. The only other possible conclusion would be based on agreement with the assumption made by some investigators, that the apparent excess of impact resilience is due to losses of energy due to vibrations set up in the machine, etc. This assumption, however, is made improbable by the fact that the ductility of specimens broken under impact is greater than that of specimens broken under slow application of load. Blount, Kirkaldy and Sankey state that in every case the "elongation" and "reduction of area" are greater in the specimens broken under impact tension than in those broken under static tension. Langenberg[2] made a series of static and impact tension tests on specimens from chrome-nickel steel forgings. The specimens used in the two kinds of test were not similar and no comparison was made between impact-resilience and static-resilience. The "reduction of area," however, was uniformly higher in the impact specimens than in the static-tension specimens. Comparison between elongations could not, of course, be made since the specimens were not of similar shape. Since ductility is evidently greater under impact than under static tension, it is not probable that the resilience under the two methods of testing is the same.

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[1] Blount, Kirkaldy and Sankey, "Comparison of the Tensile, Impact-Tensile and Repeated Bending Methods of Testing Steel," *Proceedings*, Inst. M. E., No. 2, p. 715 (1910).

[2] Langenberg, "Experimental Data Obtained on Charpy Impact Machine," *Bulletin*, Am. Inst. Min. and Met. Engrs., Aug., 1919, No. 152, p. 1471.

The question of practical importance, however, is not whether impact resilience is greater than static resilience, but whether the ratio of impact resilience to static resilience varies with the shock-resisting quality of the material. Unless this ratio varies with the toughness of the metal, an impact test has no advantage over a static test in detecting brittleness of material. Since so few experimental results are available, any conclusion reached from analysis of the data must be only tentative. The ratios obtained by Blount, Kirkaldy and Sankey apparently do not depend on the composition or toughness of the material. The ratio seems to be about the same for brittle as for ductile steel. The resilience ratios obtained by the Naval Experiment Station also do not show any dependence on the toughness of the material.

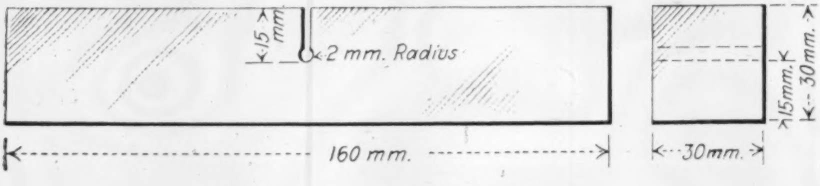

FIG. 1.—Charpy Impact Test Specimen.

In the present state of knowledge of the subject, therefore, there would seem to be no good reason to assume that static resilience tests on notched bars are inferior to impact resilience tests as a means of detecting brittleness. Further evidence, however, should be obtained on this subject by means of notched bar tests on static machines, such as the Humfrey machine or other machines having an automatic stress-strain recording device, in comparison with similar tests on impact testing machines.

DESCRIPTION OF IMPACT TEST SPECIMENS.

The International Association for Testing Materials in its meeting at Copenhagen in 1909 adopted two standard impact test specimens of similar form but different size. These specimens are shown in Figs. 1 and 2. Fremont criticized the larger specimen because it may enclose unsound parts in an envelope of better quality. He says that test specimens should be as small as possible so as to show the minimum toughness and the degree of uniformity of the material rather than its average condition. He also asserts that in this specimen the radius at the bottom of the notch is too large. He refers to his paper read at the 1900 Congress of the International Association for Testing Materials in which he states that satisfactory results can be secured by notching specimens with an ordinary saw cut. He asserts that there may be considerable latitude in the dimensions of this cut without affecting the resilience values.[1]

The British Engineering Standards Association has adopted standard specimens and subsidiary specimens of both beam and cantilever types. They have adopted for all specimens a V-shaped notch with 0.25-mm. radius at the bottom and with an included angle of 45 deg. Their 1920 report says: "Various forms of notch have been adopted by different engineers, and the work of fracture is different according to the type of notch used. It is certain that the indication of brittleness marked by a low value of the work of fracture is more definite the smaller the angle of the notch and the radius of curvature at the bottom of the notch." The standard specimens are 10 mm. square, the V notch being 2 mm. deep. The beam type of specimen is tested on a span of 40 mm. between supports; the striking distance of the pendulum in cantilever type is 22 mm.[2] The subsidiary specimens are 10 by 5 mm. in cross-section and 5 mm. square. The notch in the subsidiary specimens is V shaped 1.5 mm. deep, with a root radius of 0.25 mm. and an included angle of 45 deg. The beam specimens are tested on a span of 20 mm. between supports; the striking distance of the pendulum in the cantilever type is 11 mm.

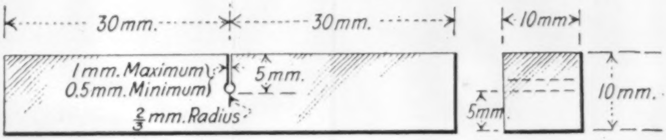

Fig. 2.—Charpy Impact Test Specimen (Small Size).

The Izod-Mesnager specimen, shown in Fig. 3, has the same dimensions as the British Engineering Standards Association cantilever specimen, but the radius of the notch is much larger.

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[1] The Fremont specimen is illustrated in Fig. 3, p. 89.—Ed.

[2] The standard beam and cantilever type specimens are illustrated in Figs. 1 (*b*) and 2 (*b*), pp. 87 and 88.—Ed.

Philpot[1] made a series of experiments to obtain a cylindrical specimen whose resilience would be equal to that of the British Association cantilever specimen. Specimens were developed 0.45 in. in diameter with a V notch 0.13 in. deep, a root radius 0.01 in., with an included angle of 45 deg.[2] Another specimen of the same diameter was developed with a V notch 0.12 in. deep, the notch being turned in an eccentric mandrel. Both of these specimens were found to be practically equivalent to the British Association's cantilever specimens.

Since not much attention has been paid to standardization of impact tension specimens there are very few such specimens in common use.[3]

EFFECT OF FORM AND SIZE OF TEST SPECIMEN ON RESILIENCE.

Since resilience specimens cannot always be made of a single standard size, many attempts have been made to correlate resilience values obtained with specimens of different forms and sizes. The results of such attempts, however, have thus far been unsatisfactory. Révillon in a paper presented to the International Association for Testing Materials in 1909 announced as a general principle that, for two geometrically similar test pieces of the same metal, the resilience per square centimeter of section should be the same. Influenced by this paper and the discussion, the Congress adopted the two geometrically similar Charpy test specimens. When Révillon's principle was investigated further, however, it was found to be incorrect. The specific resilience of the larger specimen is always greater than that of the smaller. When two similar specimens of different dimensions are deformed to a similar extent, but not to the point of fracture, the ratio of the amounts of work expended on the two specimens is equal to the ratio of the cubes of like dimensions. When the deformation is carried to the point of fracture, however, the ratio of the

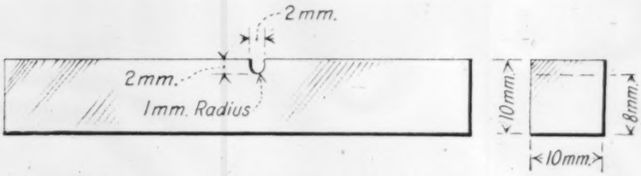

FIG. 3.—Izod-Mesnager Impact Test Specimen.

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[1] Philpot, "Some Experiments on Notched Bars," *Journal*, Soc. Automotive Engrs., Dec., 1918, Vol. III, No. 6, p. 347.

[2] This specimen is illustrated in Fig. 2 (*c*), p. 88.—ED.

[3] Two Charpy impact tension test specimens, one unnotched and the other notched, are illustrated in Fig. 5, p. 89.—ED.

amounts of work absorbed in the two cases appears to be intermediate between the ratio of the cubes and the ratio of the squares of like dimensions.

Unwin[1] in discussing the 1918 report of the British Engineering Standards Association says: "The fracture of a notched bar is of the nature of a progressive tear. The area resisting and the distribution of the resisting stress vary in the process. Probably only a very short length of the bar in the neighborhood of the fracture is in any way concerned in the deformation. These considerations throw doubt on the applicability of the dimensional law." He suggests, however, as empirical formulas that may be useful in the comparison of specimens of beam type, of different dimensions, the expressions:

$$\frac{W}{a^{\frac{5}{4}}} \text{ or } \frac{W}{bh^{\frac{3}{2}}},$$

in which W represents the resilience of the specimen, a represents the area of the reduced cross-section, b represents the breadth and h the depth of the reduced section. Unwin says that these formulas seem to agree equally well with experimental results. The exponents, however, are only approximate and vary with the material.

Most experiments on the relationship of resilience to size and form of test specimen have been made with specimens of beam or cantilever type. Since in such specimens the stress relations are very complex, it is not surprising that great difficulty has been encountered in attempts to correlate different specimens. Since in notched tension specimens the stress variations are less complex, it would seem that such specimens are more suitable for experiments in correlation.

THEORETICAL DISCUSSION OF RESILIENCE OF A NOTCHED TENSION SPECIMEN.

In discussing the effect of form of specimen on resilience, it is essential to have data in regard to the effect of abrupt change of section on stress distribution. For information on this subject the investigations of Coker and Heymans[2] have been found very useful. In studying these stress relations the present writer has found it convenient to use a mode of representation that is frequently used in illustrating direction and magnitude of magnetic forces. Stresses in material, as well as magnetic forces, can be represented by "lines of force." Direction of stress can be indicated by direction of lines of force, and magnitude of stress by the number of lines per unit sectional area.

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[1] Unwin, "Notched Bar Tests," *Engineering*, Sept. 12, 1919, p. 329.

[2] Coker and Heymans, "Stress Concentrations due to Notches and Like Discontinuities," *Engineering*, Vol. CXIII, p. 26 (1922).

By means of such "lines of force," the stress distribution in a notched bar and its effect on resilience are illustrated in Fig. 4. This figure represents a longitudinal section through a notched cylindrical bar under tension. It will be noted that near the axis the lines of force are straight and evenly spaced. As the notch is approached the lines become curved and their concentration increases. Coker and Heymans have shown that with specimens 10 mm. square in cross-section, notched half-way through with notches having different radii at the bottom, the stress at the bottom of the notch increases from twice to six times the average stress as the radius of the notch is decreased from 10 mm. to 0.6 mm. The stress concentration undoubtedly also increases with increase in the depth of the notch. Beyond a certain depth, however, the increase of stress concentration with depth is probably slight.

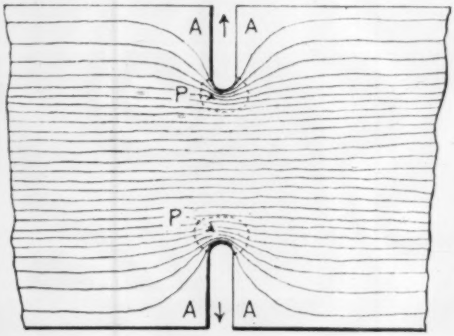

FIG. 4.—A Longitudinal Section Through a Notched Cylindrical Bar Under Tension Showing Lines of Force.

As the closely crowded lines of force leave the bottom of the notch they curve outward toward the circumference of the specimen. Practically no lines, however, enter the regions, designated by *A* in Fig. 4, near the outer circumference of the notch. In such regions the stress is practically zero. Since these regions contain no lines of force, they can be removed without changing the stress distribution or resilience. For example, J. J. Thomas[1] showed that the sides of the notch in a standard Charpy specimen can be cut away until they enclose an angle of 60 deg. without affecting the resilience.[2]

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[1] Thomas, "The Charpy Impact Test on Heat-Treated Steels," *Proceedings*, Am. Soc. Test. Mats., Vol. XV, Part II, p. 63 (1915).

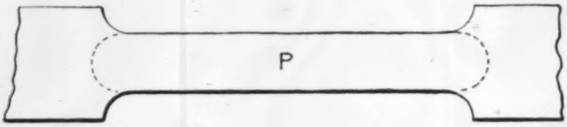
[2] See notched Charpy specimen used by Laboratory No. 4, as reported in Questionnaire presented elsewhere in this Symposium. See Table I, p. 84, and Fig. 1 (*a*), p. 87.—ED.

Radial stresses of considerable magnitude, as well as longitudinal stresses, exist in a notched bar under tension. That this is true will be evident from a study of the lines of force in Fig. 4. If it be imagined that the curved lines have a tendency to shorten, it will be apparent that radial tensile or compressive stresses will be produced according as the curvature is outwardly concave or convex. The radial stresses in the specimen illustrated in Fig. 4 are in the directions indicated by arrows. Coker and Heymans have shown that such lateral stresses actually exist in appreciable degree even in a standard tension specimen. The effects of the radial tensile stress in the section enclosed by the notch, and the radial compressive stress on either side of the notch, can be plainly seen when a notched cylindrical bar of ductile material is broken. The radial tensile stress opposes the tendency of the section enclosed by the notch to reduce in area as the specimen approaches the breaking point. Due to these opposing tendencies longitudinal fissures can frequently be seen in such specimens near the axis on the surface of fracture.

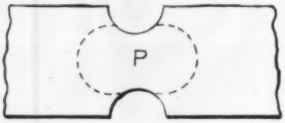
In a notched bar, therefore, the material is tested in a lateral as well as a longitudinal direction. It is probable that in a notched specimen of material deficient in transverse ductility, cracks frequently start from the bottom of the notch in a longitudinal or diagonal direction, then gradually curving, cross the specimen transversely. Resilience values as obtained with notched bars, therefore, depend on the mobility of the metal in all directions. This property of a metal may be designated by the word "plasticity."

When the stresses are within the elastic limit of the material, the stress at the bottom of the notch is several times as great as the stress near the axis. If this ratio held as the load is increased until the metal at the bottom of the notch reached its breaking point, the metal near the axis would not have reached its elastic limit. The metal within a certain distance around the bottom of the notch would have undergone plastic deformation. At the boundary of this plastically deformed region the metal would be stressed only to its elastic limit. Such regions are shown in section in Fig. 4 and are designated *P*. Actually, however, the stress gradient would change as the region around the bottom of the notch becomes plastically deformed. The shape of the plastic region undoubtedly alters as the specimen yields. Nevertheless it is evident that around the bottom of the notch is a region of maximum deformation and that the deformation of this region absorbs the greater part of the work done in breaking the specimen. When the notch is properly proportioned, the surface of fracture of a cylindrical specimen broken by tension shows an outer ring of fibrous appearance enclosing a circle of granular or crystallin appearance. Evidently in such a specimen the outer ring has been plastically deformed until cracks started, the cracks then extended to the axis accompanied by little deformation of the metal in the inner circle.

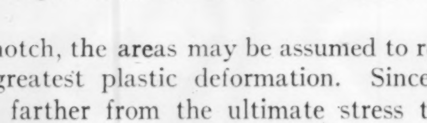
From these theoretical considerations it can now be shown that the notched bar test, if the specimen is of suitable form, is especially sensitive to variations in the plasticity of the metal. While the boundaries of the regions designated by the letters *P* in Fig. 4 represent merely the positions at which the stress is about half that at the bottom of the notch, the areas may be assumed to represent roughly the regions of greatest plastic deformation. Since in general the elastic limit is farther from the ultimate stress the more plastic the material, it follows that both the average length and average area of cross-section of the areas *P* will vary with the plasticity of the metal. Since this is the case, it can be shown that the resilience values obtained with such specimens will vary as the third power of the plasticity of the metal. In other words, a resilience test on such a bar is sensitive in the third degree to variations in plasticity.



(*a*) Specimen Sensitive in First Degree.



(*b*) Specimen Sensitive in Second Degree.



(*c*) Specimen Sensitive in Third Degree.

FIG. 5.—Longitudinal Sections Through Three Cylindrical Bars Illustrating Three Degrees of Sensitiveness to Variations in Plasticity.

What is meant by "third-degree sensitivity" may be explained by reference to Fig. 5. In Fig. 5 (*a*) the area *P* represents the metal that will be plastically deformed in breaking a standard tension specimen. In this case the volume affected is practically independent of the plasticity of the metal, since only the relatively small semicircular regions at the ends would vary with the plasticity. A resilience test with this specimen, therefore, depends merely on the ductility (and strength) of the material. The standard specimen may be said to be sensitive in the first degree to variations in plasticity.

If the portion between the fillets of the specimen shown in Fig. 5 (*a*) is removed and the two ends brought together, the specimen would have the form shown in Fig. 5 (*b*). In this specimen the dimensions of the notch are assumed to be such that the stress concentration at the bottom is relatively slight. Under these conditions, instead of two areas such as areas *P* in Fig. 4, only one area *P* of greatest plastic deformation would occur as shown in Fig. 5 (*b*). In this case, the length of the region to be plastically deformed will vary with the plasticity of the metal. The resilience value obtained will, therefore, vary as the second power of the plasticity. This form of specimen is sensitive in the second degree to variations in plasticity.

If the radius of the notch is decreased to a certain point, depending on the radius of the reduced section of the specimen, the region *P* does not extend to the center, but is as shown in Fig. 5 (*c*). The resilience value obtained with such a specimen will vary as the plasticity of the metal, as the average length of the areas *P* and as the average area of cross-section of those areas. Since the two latter factors vary with the plasticity, the resilience value obtained with this specimen will vary as the third power of the plasticity. This test specimen, therefore, is sensitive in the third degree to variations in plasticity.

The three different degrees of sensitivity described above are capable of detecting three different degrees of brittleness. Unless the metal is extremely brittle, a standard tension specimen will not break with a granular or crystallin fracture. Unless the metal is moderately brittle, a specimen of the form shown in Fig. 5 (*b*) will not break with a granular or crystallin fracture. A specimen of third-degree sensitivity, however, illustrated in Fig. 5 (*c*), will break with a fracture at least partly granular or crystallin unless the plasticity of the metal is great.

SENSITIVITY IN RELATION TO FORM OF NOTCH.

It is now possible to state qualitatively a few conclusions in regard to the relation of depth and radius of notch to the sensitivity of a resilience specimen. Evidently, to produce localization of stress, the depth of the notch must be great enough so that the reduced section of the specimen can be broken without stressing the unreduced section beyond its elastic limit. For tension specimens, therefore, the ratio of the area of reduced section to that of unreduced section should not be greater than about one-half. For a rectangular beam or cantilever specimen, the ratio of the two sections should not be greater than about four-fifths. (This is the ratio in the British Association specimens.)

The proper radius of the notch in a notched cylindrical tension specimen depends on the radius of the reduced section. If the ratio of notch radius to radius of reduced section is too large, the region of greatest plastic deformation will have the form shown in Fig. 5 (*b*), and the specimen will have second-degree instead of third-degree sensitivity. The effect of variations in this ratio on resilience sensitivity is now being investigated quantitatively at the Naval Engineering Experiment Station.

IMPACT TESTS OF WOOD.

By Thomas R. C. Wilson.[1]

As far as the writer knows, no other agency has given to the impact testing of wood as much attention as has the United States Forest Service, with which organization he is connected.[2] Consequently, this paper will be devoted chiefly to a discussion of the work of the Forest Service along this line.

The first work of the Forest Service with impact tests of which record is available began some twenty years ago with the construction, under the direction of Professor W. K. Hatt, at the laboratory then maintained at Purdue University, of a machine[3] especially designed for the impact testing of wood. This machine, with later modifications as worked out by the Forest Service, is shown in Fig. 1. It consists essentially of a "hammer" sliding between vertical guide columns. The hammer is raised by an electric magnet which is pulled up or lowered as desired by a mechanism driven by a motor mounted on the top of the columns. Current for the magnet coil is furnished by a small dynamo driven by the same motor. The hammer is let drop when the magnet circuit is broken with the throwing of a switch on the magnet by a tripping pin. This tripping pin slides on a scale attached to one of the guide columns and is capable of being set at any desired position. The scale itself is movable vertically for adjustment. The base of the machine consists of a heavy casting to which the guide columns are bolted and whose upper face is slotted to receive attachments for supporting the specimen. Mounted on the base of the machine and near the guide columns is a brass drum or hollow cylinder. This drum is free to rotate about a vertical axis and is so positioned that a stylus carried by the hammer can be pressed against its surface by a spring. An arrangement is provided for mounting a tuning fork in such a manner that a stylus fixed to one of its prongs may be pressed against the drum. The machine is equipped with hammers weighing 12½, 25, 50, 100, and 200 lb. A detachable rounded striking block is attachable to the lower end of each of these hammers for use in flexure tests. A similar flat-faced block is available for use in compression tests. The hammer can be dropped from a height of approximately 6 ft.; consequently the capacity of the machine is 75, 150, 300, 600, or 1200 ft-lb., depending on which of the hammers is used. The weight of the entire machine is approximately 5500 lb.

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[1] Engineer in Forest Products, Forest Products Laboratory, Forest Service, U. S. Department of Agriculture, Madison, Wisconsin.

Acknowledgment is made to Mr. J. A. Newlin, In Charge, Section of Timber Mechanics, Forest Products Laboratory, for valuable assistance in the preparation of this paper.

[2] The increment drop test in the Hatt-Turner machine has been used by the Forest Products Laboratories of Montreal, Canada, for several years in a series of standard tests of Canadian woods.

[3] This machine was described by W. K. Hatt and W. P. Turner in an article "The Purdue University Impact Machine" published in *Proceedings*, Am. Soc. Test. Mats., Vol. VI, p. 462 (1906). The machine is referred to in this paper as the Hatt-Turner machine.

In flexure tests the blow of the hammer is received at the center of a beam of simple span. Each end of the beam sets loosely in a "shoe" which is free to turn on supporting knife edges of rounded form. The shoes are of sufficiently small mass that the energy absorbed as they turn slightly with the deflection of the beam is negligible.

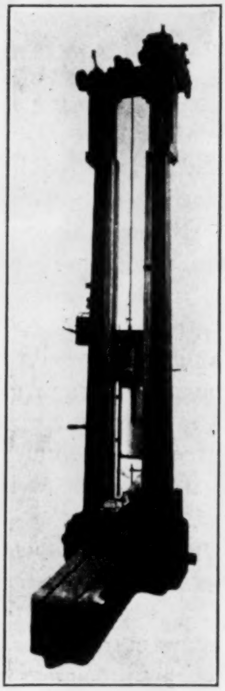

FIG. 1.—Hatt-Turner Impact Machine as Used by the U. S. Forest Service.

Two kinds of flexure impact tests have been made on this machine:

1. Single-drop tests in which the specimen is completely fractured by a single blow; and
2. Increment-drop tests in which the hammer is allowed to fall from successively increasing heights until failure occurs.

The procedure in making these tests is as follows:

Single-Drop Test.—The specimen is placed in position, and while the hammer (without the magnet) rests on it the drum is rotated, and the stylus attached to the hammer traces a datum line on the paper affixed to the drum. The tripping pin is set at a height of fall which it is estimated will produce complete fracture of the specimen with little unexpended energy remaining in the hammer. While the hammer is being raised the drum is set rotating. The hammer is then released and as it descends past the rotating drum the tuning fork is set in vibration and the stylus attached to it pressed against the drum (an adjustable stop enables the proper pressure to be predetermined and used). A piece of metallized paper wound about the drum receives the trace of the tuning fork. As the hammer falls, the stylus attached to it is engaged by a guide which releases it after it has passed the upper end of the drum and allows a spring to press it against a sheet of paper covering the drum. This paper being backed by a sheet of carbon paper receives a trace of the path of the stylus which is attached to the hammer.

It is evident that this trace of the hammer stylus, together with the trace of the stylus attached to the tuning fork, constitutes a space-time curve for the hammer.

Increment-Drop Test.—After placing the beam in position the hammer, without the magnet, is allowed to rest on it while the drum is rotated and the stylus attached to the hammer traces a datum line on the record sheet mounted on the drum. The hammer is then raised for the first drop and as it falls upon the stick the operator turns the drum slightly while the hammer is coming to rest in order to get separate and distinct stylus traces of the height of drop (as long as this does not exceed the height of the drum), of the deflection produced by the drop, and of the position of the hammer after it has come to rest on the stick. Such a record is taken for each drop until it is certain that the elastic limit is passed. The usual practice is to make the first drop 1 in., then increase by increments of 1 in. until a height of drop of 10 in. is reached. After this, 2-in. increments of drop are used until complete fracture of the specimen occurs. Fig. 2 shows the record as traced by the stylus on a sheet affixed to the drum.

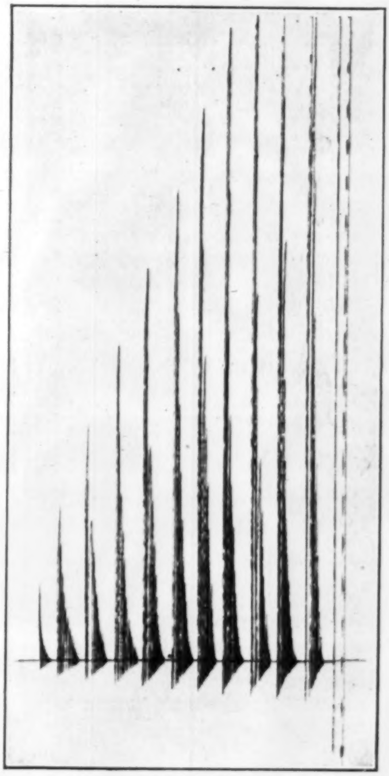

FIG. 2.—Sample Drum Record of Increment-Drop Test.

The quantities obtained from these tests are: Modulus of elasticity, fiber stress at elastic limit, work absorbed to elastic limit, and height of drop causing complete failure. The principal computations are described and illustrated in the Appendix.

As was previously mentioned, the records made on paper affixed to the drum in the single-drop test constitute a space-time curve for the hammer. The first and second differential curves of this space-time curve will be velocity-time and acceleration-time curves, respectively. From the data of the drum record time can be replaced by deflection, and from the known masses of hammer and specimen and the relation between acceleration, mass and force, acceleration can be replaced by force. If then the differential curves could be constructed the pressure between the hammer and the specimen at all stages of the test could be computed and a graph similar to the ordinary load-deflection graph as derived from static-bending tests could be produced. From this graph, data for computing fiber stress at elastic limit, modulus of elasticity, modulus of rupture, and energy required to break the specimen could be taken. As will be recognized, the obstacle in such a procedure is the very considerable difficulty of constructing differential curves that accurately represent the original space-time curve, particularly at those points of change of curvature which are especially significant in locating the elastic limit and maximum load in the force-deflection curve. When the machine was first designed, considerable study was given to the problem of constructing the differential curves referred to. No completely satisfactory means for doing this were found. Furthermore, careful study of single and increment drop on the basis of comparative tests led to the conclusion that the property measured by the increment test was of fully as great practical significance with respect to wood as that measured by a single-drop test, and the increment-drop test was adopted and has been used as standard by the Forest Service for a number of years. The comparative significance of single-drop and increment-drop tests as applied to wood will be the subject of further discussion later in this paper.

Simple, accurate means are available for drawing tangents to the parts of the space-time curve representing approximately free fall conditions. Consequently, determinations can be easily made of velocity of hammer before contact with the stick, for the purpose of calibrating the machine, and after complete failure of the stick, for the purpose of determining the energy consumed by the stick.

In connection with the problem of constructing the differential curves from the space-time curve produced in the single-drop test and thus arriving at a knowledge of the force exerted upon the stick by the hammer at each instant from first contact until complete rupture, reference is made to some experiments carried out a few years ago by Mr. Armin Elmendorf.[1] Mr. Elmendorf tested a number of specimens in single-drop on the Hatt-Turner machine and by means of a differentiating machine of his own invention, constructed the two differential curves of the space-time curve, and plotted force-deflection curves from which it was possible to compute all of the quantities usually derived from static bending tests. Static bending tests were also made on specimens cut from the same boards as the impact specimens. As was to be expected, comparison showed the values under the impact test to be considerably higher than were obtained in the static test, the maximum load being about 75 per cent higher, deflection at which maximum load occurred 25 per cent higher, and work consumed up to maximum load 100 per cent higher. The force-deflection curves had the same general form as load-deflection graphs derived from static bending, although not exactly similar since the ordinates of the force-deflection graph exceed the ordinates of the load-deflection graph by a greater percentage than do the abscissas. Thus there is some indication that the energy absorbed by the stick in the impact test does not indicate any different property than does the energy absorbed in a static test. However, generalization along this line is not justified by tests on a single species and particularly from a single board, as were the specimens compared in these tests. Comparison was also made of the energy consumed as determined from the difference of kinetic heads before and after breaking the specimen plus the work done by gravity during the deflection with the area under the force-deflection curve. These comparisons for six beams showed that the maximum value of the energy unaccounted for by the area under the force-deflection curve was about 5 per cent.

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[1] Armin Elmendorf, "Stresses in Impact," *Journal of the Franklin Institute*, December, 1916.

Mr. Elmendorf is using some of the same data in a discussion contributed to this Symposium. See p. 117.—ED.

While the tests were not sufficiently numerous to permit a computation of average or probable value of the loss of energy, and the results were further subject to error in the differentiating process, they indicate that the energy loss due to vibrations and to the indenting of the specimens by the hammer and supports are within reasonable limits.

COMPARISON OF SINGLE-DROP AND INCREMENT-DROP IMPACT TESTS.

Recently the author has made a number of tests for comparison of single and increment-drop tests. The test specimens included a number of pairs of sticks from each of several species. A pair consists of two sticks which were cut from larger pieces in such a manner that they are either end to end or side by side and include the same annual growth layers; consequently, the sticks of each pair are as nearly inherently alike as can be secured. One stick of each pair was tested by increment-drop in the Hatt-Turner machine. The other stick of each

TABLE I.—COMPARISON OF ENERGY ABSORBED IN SINGLE-DROP IMPACT TESTS WITH DROP REQUIRED TO PRODUCE COMPLETE FAILURE UNDER INCREMENT-DROP IMPACT.

Species.	Increment-Drop Tests (Purdue Machine).				Single-Drop Tests.							
					Purdue Machine.				Russell Pendulum Machine.			
	Stick No.	Specific Gravity.	Moisture, per cent.	Maximum Drop, in.	Stick No.	Specific Gravity.	Moisture, per cent.	Energy Absorbed, in-lb. per cu. in.	Stick No.	Specific Gravity.	Moisture, per cent.	Energy Absorbed, in-lb. per cu. in.
Yellow poplar....	1...	0.342	14.0	8	2...	0.356	13.6	10.2				
	3...	0.406	12.6	10	4...	0.405	11.9	13.3				
	5...	0.376	9.8	9					6...	0.389	9.6	9.7
	7...	0.354	14.0	6	8...	0.368	9.6	11.2				
	9...	0.368	11.8	7					10...	0.397	8.9	9.3
	11...	0.412	9.9	10	12...	0.422	11.3	19.0				
	13...	0.444	9.5	12					14...	0.462	9.5	15.7
	15...	0.379	9.0	8	16...	0.373	11.4	12.8				
	17...	0.394	9.0	10					18...	0.399	9.1	12.0
Southern yellow pine	21...	0.588	10.0	12	22...	0.616	11.3	13.5				
	23...	0.603	12.0	10					24...	0.563	12.5	15.1
	25...	0.549	13.1	14	26...	0.552	12.3	14.9[a]				
	27...	0.498	13.0	16	28...	Cull						
	29...	0.515	11.0	12					30...	0.533	8.9	18.6
	31...	0.650	9.3	18	32...	0.614	11.0	24.5				
	33...	0.566	10.9	16	34...	0.533	11.5	18.0				
	35...	0.572	12.6	18					36...	0.610	11.1	24.5
	37...	0.688	13.4	14	38...	0.722	11.5	13.4[a]				
	39...	0.574	12.7	22	40...	0.586	11.7	41.0				
	41...	0.558	14.1	20					42...	0.584	10.6	22.1
	43...	0.506	14.4	16	44...	0.525	11.9	23.4				
	45...	0.497	12.6	14					46...	0.533	12.3	16.7
Cork elm....	51...	0.587	13.8	22	52...	0.561	15.9	55.6				
	53...	0.616	14.9	28					54...	0.578	14.5	42.3
	55...	0.727	15.5	40	56...	0.730	15.4	71.3[a]				
	57...	0.724	14.0	38					58...	0.762	15.3	80.3
	59...	0.654	16.4	28	60...	0.689	11.1	63.2				
	61...	0.640	14.9	32					62...	0.668	12.5	67.5[b]
	63...	0.672	....	28	64...	0.629	12.3	60.8				
Oak........	71...	0.603	13.8	9	72...	0.608	12.5	25.0				
	73...	0.524	10.3	12					74...	0.513	9.1	14.1
	75...	0.560	11.9	10	76...	0.546	12.1	19.1				
	77...	0.670	12.5	9					78...	0.540	9.5	14.1
	79...	0.554	12.5	5	80...	0.556	12.6	9.4				
	81...	0.600	10.0	18					82...	0.579	10.9	31.0
Douglas fir..	91...	0.455	11.9	14	92...	0.445	12.0	21.3				
	93...	0.445	11.8	16					94...	0.444	14.5	17.1
	95...	0.451	10.5	12	96...	0.457	12.6	15.4				
	97...	0.438	14.6	6					98...	0.452	12.0	11.5[d]
	99...	0.460	12.0	12	100...	0.457	13.9	19.8				
	101...	0.454	12.0	7					102...	0.426	14.5	15.2
	103...	0.453	....	14	104...	0.434	13.6	18.7[a]				
Sitka spruce	111...	0.386	14.0	8	112...	0.389	13.2	12.5				
	113...	0.402	12.1	10					114...	0.409	12.0	12.0
	115...	0.346	12.8	12	116...	0.358	10.6	19.4				
	117...	0.354	10.7	12					118...	0.360	9.0	14.8
	119...	0.368	10.6	10	120...	0.363	11.6	22.5[a]				
	121...	0.370	12.4	12					122...	0.376	12.0	18.4
	123...	0.369	12.6	12[c]	124...	0.368	11.0	22.9				
Greenheart..	131...	0.837	21.4	20	132...	0.879	20.3	53.4				
	133...	0.840	30.0	24					134...	0.887	27.8	21.1
	135...	0.861	25.6	12	136...	0.869	22.4	48.1				
	137...	0.859	23.0	24					138...	0.868	21.5	[e]
	139...	0.820	21.0	22					140...	0.806	21.0	46.4
	141...	0.841	28.2	20	142...	0.914	22.0	40.2				
	143...	0.797	20.0	18	144...	0.787	21.0	29.1				
	145...	0.814	20.4	26					146...	0.823	20.8	50.4

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[a] Not completely broken.

[b] Swing of hammer after passing through stick interfered with.

[c] Slightly defective.

[d] Received rather severe blow accidentally before test; no injury apparent except indentation.

[e] Test imperfect.

pair was tested in single-drop, slightly more than half of these tests being made in the Hatt-Turner machine, and the remainder in a Russell Pendulum machine belonging to the University of Wisconsin. The 100-lb. hammer was used in the Purdue machine. The Russell machine had a striking weight of 185 lb. with the centers of gravity and percussion 23.5 and 33.6 in., respectively, from the center of suspension. The specimens were set in such a position as to be struck by the weight at its center of percussion. Sticks tested in the Hatt-Turner machine

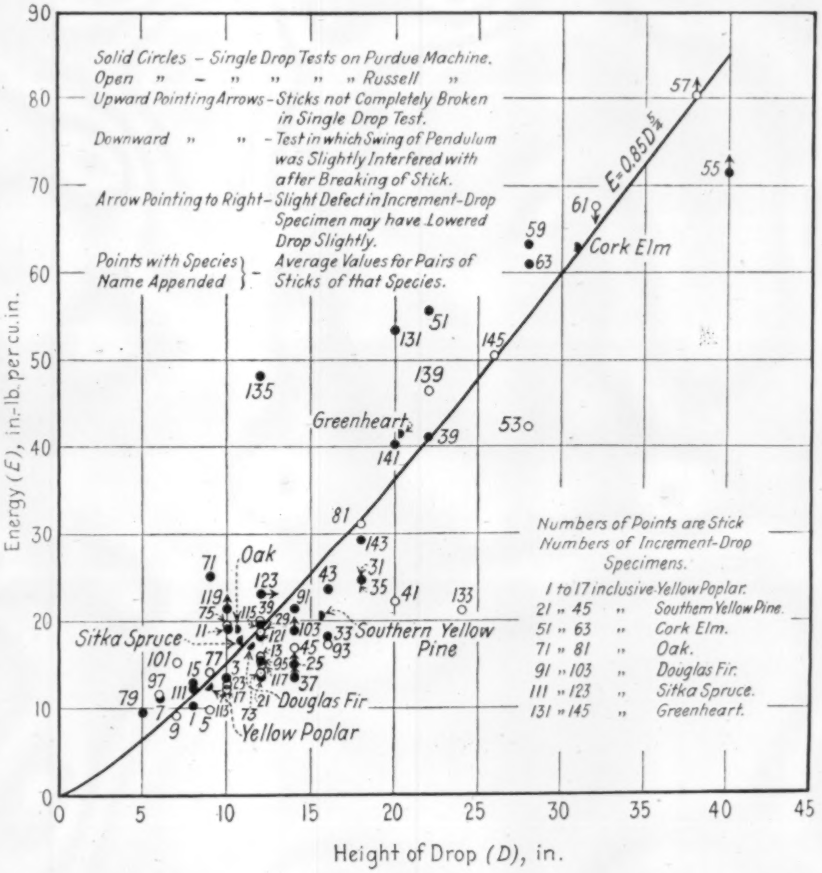
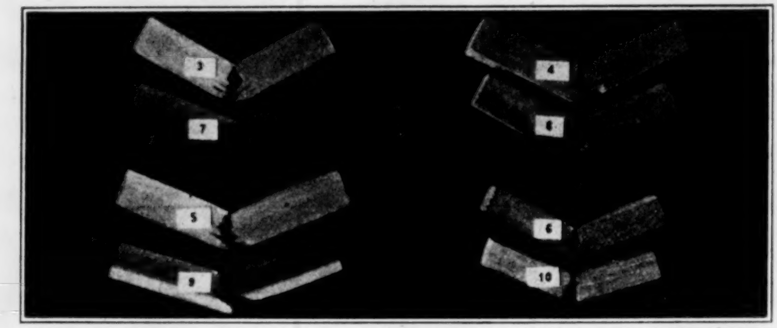


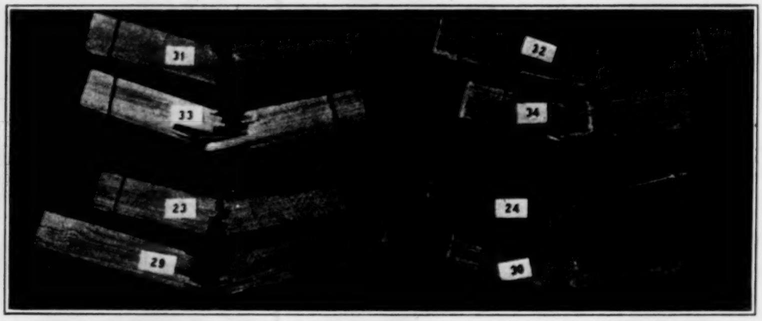
FIG. 3.—Comparison of Single-Drop and Increment-Drop Impact Bending Tests.

D=Height of drop required to cause complete failure in increment-drop test of a 2 by 2-in. stick on a 28-in. span—Hatt-Turner machine—100-lb. hammer.

E=Energy absorbed by similar sticks when broken in a single-drop test.



(*a*) Yellow Poplar.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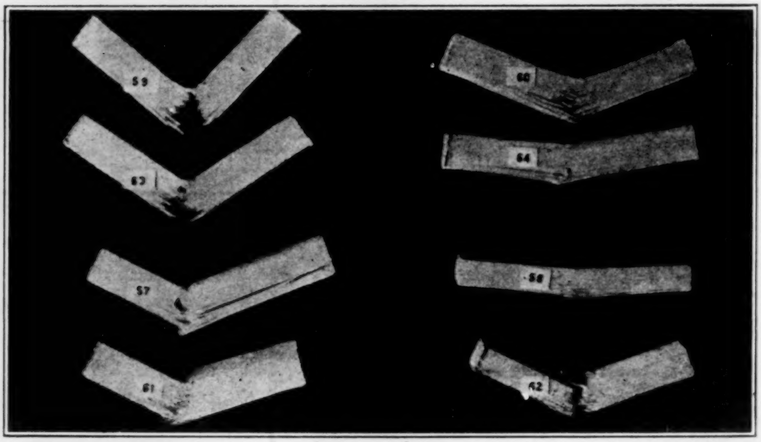
30

(*b*) Yellow Pine.

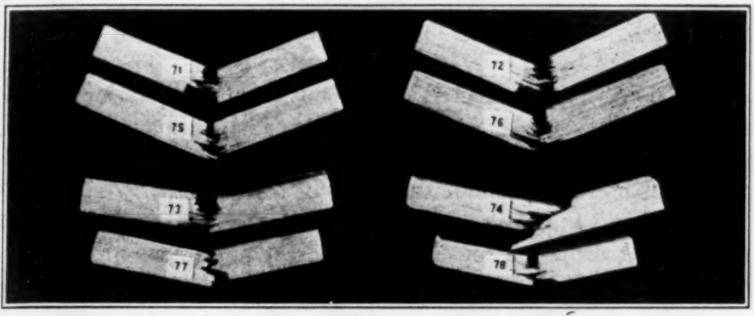

59
63
57
61
60
64
58
62

(*c*) Cork Elm.

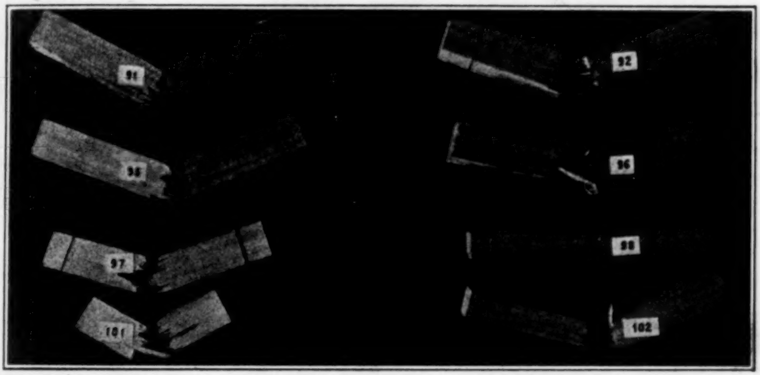
Increment-Drop Test. Single-Drop Test.

FIG. 4.—Failures of Specimens Tested in Increment-Drop and Single-Drop Impact Bending.

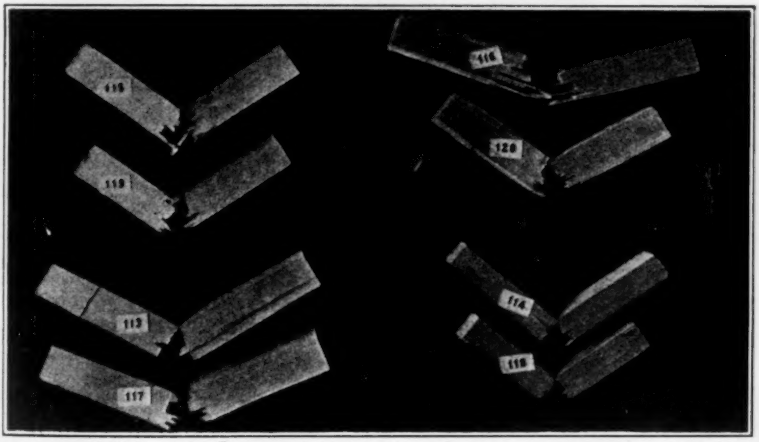
All increment-drop tests were made in the Hatt-Turner machine. The two upper specimens of each species in the single-drop test were tested in the Hatt-Turner machine and the two lower specimens in the Russell pendulum machine.


71
72
75
76
73
74
77
78

(*a*) Oak.


91
92
95
96
97
98
101
102

(*b*) Douglas Fir.


115
116
119
120
113
114
117
118

(*c*) Sitka Spruce.

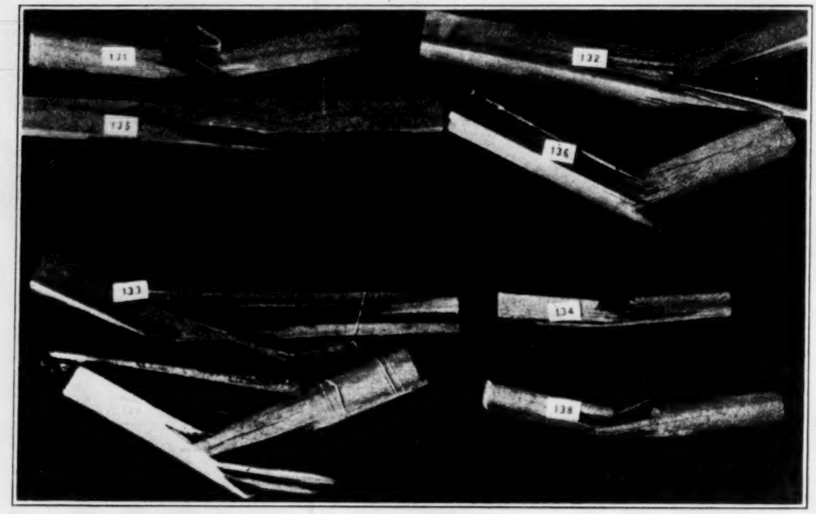
Increment-Drop Test. Single-Drop Test.

FIG. 5.—Failures of Specimens Tested in Increment-Drop and Single-Drop Impact Bending.

All increment-drop tests were made in the Hatt-Turner machine. The two upper specimens of each species in the single-drop test were tested in the Hatt-Turner machine and the two lower specimens in the Russell pendulum machine.

were 2 by 2 by 30 in. with a 28-in. span. Those tested in the Russell machine were $1\frac{1}{2}$ by $1\frac{1}{2}$ by 27 in. on a span of 24 in. The species and specimens used were so selected as to furnish a large variation in work-absorbing ability. Since the 100-lb. hammer with the maximum drop possible was required to break some of the toughest specimens this hammer was used throughout the series of tests.

Table I and Fig. 3 show the results of the tests comparing single and increment drop. Typical failures of the specimens are shown in the photographs, Figs. 4 to 6, inclusive. These photographs of failures show that the two sticks of a pair gave in most cases very similar failures, thus indicating that the sticks were inherently very much alike. In the case of the greenheart, Fig. 6, the sticks of a pair differ considerably from each other in the appearance of the failure. This is particularly true of pairs Nos. 133–134 and 135–136, which are the two pairs that give the most erratic results as is shown by Fig. 3.



Increment-Drop Test. Single-Drop Test.

FIG. 6.—Failures of Specimens of Greenheart Tested in Increment-Drop and Single-Drop Impact Bending.

All increment-drop tests were made in the Hatt-Turner machine. Specimens Nos. 132 and 136, single-drop test, were tested in the Hatt-Turner machine, and specimens Nos. 134 and 138 in the Russell pendulum machine.

In Fig. 3 the curve representing the equation $E = 0.85\ D^{\frac{5}{4}}$ has been drawn, in which D = height of drop, in inches, required to cause complete failure in the increment-drop test and E = energy, in inch-pounds per cubic inch, absorbed when broken in a single-drop test.

From a plot of the points on logarithmic paper it was found that this equation best expresses the average relation between the maximum drop in the increment tests and the energy absorbed in the single-drop tests. The departures of the plotted points from this curve correspond very closely to the normal variation to be expected between sticks paired as in these tests and it is believed that the curve represents quite accurately the results which would be secured if fully identical specimens could be tested by the two methods.

Study of results of extensive tests made at the Forest Products Laboratory on some 150 species[1] of American woods shows that "total work"[2] values in static bending are related to the maximum drop values in the increment-drop impact test in much the same way as is energy absorbed in single-drop as shown by Fig. 3; that is, energy absorbed in single-drop impact and work absorbed to complete failure in static bending are not in a simple proportion to the height of drop in the increment test but vary as a power, greater than unity, of the latter.

TABLE II.—COMPARISON OF WORK ABSORBED BY SPECIMENS UNDER STATIC-BENDING AND SINGLE-DROP IMPACT BENDING TESTS.

Species.	Static Bending.				Single-Drop Impact Bending.			
	Stick No.	Specific Gravity.	Moisture, per cent.	Work Absorbed to Complete Failure, in-lb. per cu. in.	Stick No.	Specific Gravity.	Moisture, per cent.	Work Absorbed to Complete Failure, in-lb. per cu. in.
Yellow poplar....	204	0.436	9.3	12.29	207	0.430	12.6	18.8
	205	0.441	9.0	13.64	208	0.429	12.5	19.4
Douglas fir........	214	0.495	14.9	31.81	215	0.500	14.0	29.2
	218	0.500	13.4	41.20	...	.....	....	....
Cork elm.........	228	0.764	12.3	79.00	227	0.792	12.3	116.0[a]
	229	0.798	12.5	80.00	226	0.760	16.0	109.0

[a] Not completely broken.

A few recent tests compare single-drop tests made in the Purdue machine with static bending tests on control specimens as nearly identical with those tested in impact as could be secured. This comparison is given in Table II. These data give indication of fairly close agreement between the static and single-drop impact tests with respect to work required to produce complete failure. Failures of the specimens are shown in Fig. 7.

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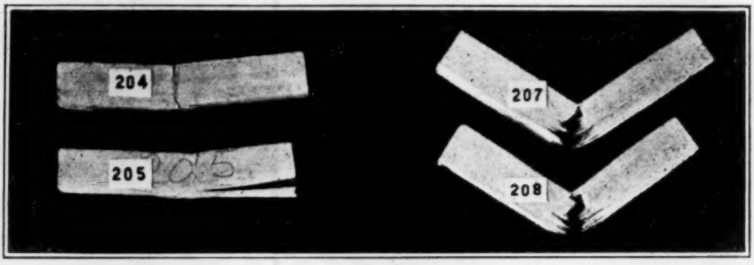
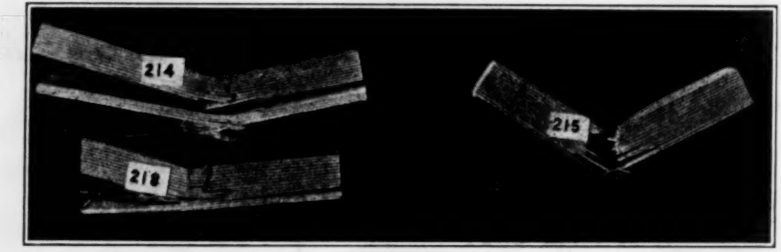
[1] Results of tests on 126 species are given in *Bulletin No. 556*, U. S. Department of Agriculture.

[2] Total work is measured by the area under the load-deflection curve when this is continued to complete failure of the specimen. In the case of static bending tests on 2 by 2-in. specimens with center load over 28-in. span decrease of the load to 200 lb. or increase of the deflection to 6 in. are arbitrarily adopted as criteria of complete failure. The test is discontinued when either of these points is reached.

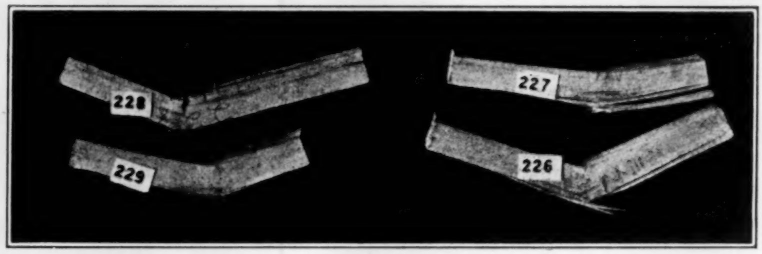
The general conclusions with respect to static bending and single-drop and increment-drop impact bending tests of wood are that "total work" in static bending, energy absorbed in single-drop impact and



(*a*) **Yellow Poplar.**



(*b*) **Douglas Fir.**



(*c*) Cork Elm.

Static Test. Single-Drop Test (Hatt-Turner Machine)

FIG. 7.—Failures of Static and Single-Drop Impact Specimens Listed in Table II.

height of drop required to produce complete failure under increment-drop impact are all measures of ability to absorb energy under shocks which produce complete failure and of ability to endure the repetition of lesser shocks straining beyond the elastic limit and producing permanent deformations and partial failures.

The three tests do not, however, give simply proportional measures of this property, which is commonly called toughness.

Although no simple proportion between the results of these three tests may exist and there may be some question as to which, if any, gives the correct numerical comparison between species, the important fact is that the species will be arranged in the same order by the three tests if these are applied to specimens properly selected and of sufficient number to be truly representative. Also individual specimens would be arranged in the same order whichever of the three tests was used.

In the woods of highest shock resistance a large proportion of the shock resistance is developed after passing the elastic limit. The contrary is true of sticks of low toughness; consequently the latter have an advantage under increment-drop tests since the number of drops applied after the elastic limit is passed and actual damage to the stick begins to occur is much less than in the woods of highest shock resistance. For this reason it is perhaps a fact that when the drop used to cause complete failure in the increment test is used as the basis of comparison the true magnitude of the difference between tough and brittle specimens is not shown. This, however, does not make the test any less valuable as a means of classifying species or specimens in their proper order with respect to shock-resisting ability.

Values of fiber stress at elastic limit as obtained from the increment-drop test show, as do numerous other tests, that the strength values developed in wood increase very materially with increase in the rate at which strain is applied. For air-dry wood, fiber stress at elastic limit as obtained from the impact test averages nearly twice as great as the same quantity from static bending tests and about 35 per cent higher than modulus of rupture. Elastic resilience averages nearly three times as great as in static bending. These comparisons are based on the tests of 126 species previously mentioned.

While a knowledge of shock-resisting ability is of great importance in connection with the many and varied uses of wood, no numerical measure of this property can be applied directly to the design of wooden members. On the other hand, modulus of elasticity and fiber stress at elastic limit as obtained under impact loading are directly applicable to design problems and very desirable to be determined. Economy in the use of test material and the need in standard tests of wood to get specimens for numerous tests from specified parts of trees requires that the number of kinds of tests for which separate specimens must be secured be kept to a minimum. Furthermore, it is usually desirable to select specimens from which different properties are to be determined in such a manner that they will be as nearly identical as possible. In the absence of simple and practical means for obtaining modulus of elasticity and fiber stress at elastic limit from single-drop tests, the increment-drop method is the more desirable from this standpoint, since by its use these properties as well as shock-resisting ability can be measured. These considerations led the United States Forest Service to adopt the increment-drop method in its program of standard tests to determine strength values for American woods.

A NEW MACHINE FOR SINGLE-DROP IMPACT TESTS.

As an acceptance test for the elimination of brittle and unreliable material the single-drop method is undoubtedly the simplest. The Forest Products Laboratory is now engaged in the design of a machine for measuring the energy absorbed in breaking small specimens of wood. This machine is of the pendulum type, but instead of the hammer or pendulum impacting directly upon the specimen, as is customary in a machine of this type, the latter passes through a small yoke which is pulled by a flexible steel cable attached to the periphery of a pulley fixed to the axis of suspension.[1] The expectation is that this machine will be used in making acceptance tests for wood for use in airplane and propeller construction, the object being to eliminate material which though it may have good static strength and stiffness is brittle, subject to sudden failure, lacking in shock-absorbing ability, and unreliable. The machine is adapted to the testing of small specimens (1 by 1 by 12 in. and smaller). Several hundred tests are being carried out to standardize the operation of this machine and to determine minimum values for use as a criterion for acceptance or rejection of material. It is expected to use specimens of uniform cross-section. Tests will be made to determine whether best results are to be secured by applying the impact at the center of the span or at two points symmetrically-spaced—as at third or quarter points. It will also be necessary to give careful attention to the form of the parts impacting upon the specimen in order to avoid undue local crushing which would lead to erroneous results.

Such a test method as this is for a number of reasons very well adapted to the purpose of acceptance tests to be made at wood-working establishments. The apparatus is relatively simple as compared to that required for other tests such as static bending; it can be easily operated by hand, hence can be placed where convenient without respect to sources of power; specimens are small and can be so taken as to very closely represent the beam, propeller lamination, or other part to be passed upon; speed of test is automatically regulated and need not enter as a factor affecting results; results are less affected than those of other tests by differences of moisture content of the wood; and so long as variations of moisture content do not exceed reasonable limits no adjustment of results is necessary.

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[1] By this means the force applied to the beam specimen under test is at all deflections uniformly applied across the width of the beam, while in the usual pendulum machine the force is thus uniformly distributed only at the instant of first contact and becomes increasingly eccentric as the deflection increases.

OTHER IMPACT TESTS.

As far as the writer knows, no extensive impact tests of wood have been made by any single agency other than the United States Forest Service. During the war the British Air Service required an impact test to be made on samples of woods to be used in aircraft construction. The test specimen was of notched cantilever form and tests were made in a machine of the Izod type. It is said that this test was required while the static bending test, which was also specified, was optional.

Recently the Bureau of Standards made a study of impact tests of wood. A total of about 200 tests were made on specimens of various forms and sizes cut from eight boards of spruce.[1] Tests were made in Izod and Charpy machines and a few static bending tests were also made. Included in the tests were specimens without notches and with notches of five different forms. One of the principal conclusions reached is that "the specimen for the Izod machine always fractures in the same way, and, therefore, the results on different materials may be compared." Every piece of wood has a characteristic failure when broken in such a manner that the failure can develop without restraint and it is the writer's belief that any test which forces failure of all specimens to occur in the same manner is likely to lead to erroneous conclusions. It is believed that any test to be useful and give valuable results must permit specimens to fail in a characteristic manner and particularly must not force localized failure at points of sudden change of cross-section as in notched-bar tests. For instance, hickory has long been recognized as the wood possessing shock-resisting ability in the highest degree. This preeminence is due to a large extent to the fact that when subjected to severe strain hickory yields not only at the section of maximum moment but for some distance on each side of this point. For instance, 2 by 2-in. sticks of hickory tested in flexure have been found by microscopic examination to have developed compression failures for some distance on either side of the load point as well as immediately adjacent to it. In general, it may be said that the woods of highest shock resistance are highest in this respect because they take a different form under bending forces than do the woods of lesser shock resistance; consequently, a test which forces local failure at a point of abruptly reduced cross-section is of very questionable value as a test for toughness of wood. During the early work in connection with the development of the Forest Service tests notched flexure specimens were experimented with. It was found that tests of such specimens did not give true comparisons of species. The form of notch used, however, differed from that of the ordinary notched bar specimen in that it extended in from all four faces of the stick.

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[1] *Technical Note No. 78*, National Advisory Committee for Aeronautics.

Some tests of notched bars of wood were made by Mr. S. Bent Russell in connection with the development of his pendulum impact testing machine.[1] A tabulation of average results of from two to six specimens of each of several species is given. These results are far from showing a true comparison of these species. This can not, however, be attributed positively to the form of the test specimens since they may not have been representative of the species.

Tests in an autographic and automatic impact testing machine of the vertical type,[2] constructed some years ago by the Forest Service, may be mentioned. This machine was so constructed that drops up to 3 ft. could be made with hammers weighing from 500 to 1500 lb. It was arranged to be automatic with respect to increment-drop tests or repeated drops from a specified height. In preliminary tests on this machine green Douglas fir specimens were tested in flexure by the repeated drop method with the number of drops varying from 100 to 8000. The weight of the hammer used was approximately one-third the load which would have broken the specimen in the usual static bending test. The drop was 0.02 in. Following the repeated drop test each specimen was subjected to standard static bending tests. The results from these tests were then compared with results of static-bending tests which had been made on control specimens cut in such a manner that they involved approximately the same annual growth layers. These comparisons indicated no significant change in modulus of elasticity, fiber stress at elastic limit, or modulus of rupture in specimens subjected to drops up to 8000 in number.

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[1] *Transactions*, Am. Soc. C. E., Vol. 39.

[2] Forest Service Automatic and Autographic Impact Testing Machine, designed by McGarvey Cline and Rolf Thelen; *Proceedings*, Am. Soc. Test. Mats., Vol. VIII, p. 538 (1908).

APPENDIX.

FORMULAS FOR INCREMENT-DROP IMPACT.

It is assumed that the elastic curve is the same as in static bending and that the relation of the force between the hammer and the specimen to the deflection is the same as the relation of load to deflection in static bending.

Let

W = weight of the hammer, in pounds;

H = distance, in inches, through which the hammer descends (including the deflection);

Δ = deflection, in inches, produced by a blow which does not stress the stick beyond the elastic limit (corresponding to H);

P = pressure, in pounds, of the hammer on the stick when deflection Δ is reached;

d = deflection, in inches, produced by the weight of the hammer resting on the stick (see Fig. 8);

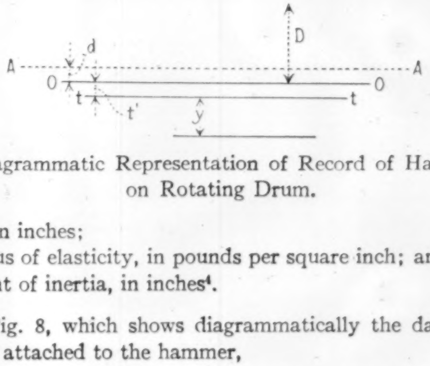

FIG. 8.—Diagrammatic Representation of Record of Hammer Stylus on Rotating Drum.

l = span, in inches;

E = modulus of elasticity, in pounds per square inch; and

I = moment of inertia, in inches^4.

Referring to Fig. 8, which shows diagrammatically the data recorded on the drum by the stylus attached to the hammer,

A-A is the true zero line—representing the position of the stick when free from stress;

O-O is the datum line drawn with the hammer resting on the stick;

t-t is the "set" line representing the position of the hammer after coming to rest following a drop;

t' = the "set," which consists principally of the indention of the stick by the hammer;

D = height of fall above zero line O-O; and

y = deflection below the set line t-t of the preceding drop.

Then

$$WH = \text{work done by the hammer.}$$

For drops which do not pass the elastic limit,

$$\frac{P\Delta}{2} = WH \qquad (1)$$

$$\Delta = \frac{P\,l^3}{48\,E\,I} \qquad (2)$$

$$d = \frac{W\,l^3}{48\,E\,I} \qquad (3)$$

From Eqs. 2 and 3,

$$P = \frac{\Delta}{d}\,W \qquad (4)$$

From Eqs. 1 and 4,

$$\Delta^2 = 2\,d\,H \qquad (5)$$

From Fig. 8,

$$H = D+t'+y \qquad (6)$$

and

$$\Delta = y+d \qquad (7)$$

since the set is not part of the deflection.

Substituting Eqs. 6 and 7 in Eq. 5,

$$(y+d)^2 = 2\,d\,(D+t'+y) \qquad (8)$$

Simplifying,

$$D = \frac{y^2}{2\,d} + \left(\frac{d}{2} - t'\right) \qquad (9)$$

The quantity $\left(\frac{d}{2}-t'\right)$ in Eq. 9 is negligible in comparison with D for drops within the elastic limit.

Hence, the equation

$$D = \frac{1}{2d}\,y^2 \qquad (10)$$

may be used and if values of D are plotted as ordinates with values of y^2 as abscissas the resulting graph will, for points within the elastic limit, be a straight line through the origin with slope of $\frac{1}{2\,d}$ and the elastic limit will be where y^2 begins to increase more rapidly than D.

In working up results of an increment drop test from the drum record, the first few drops are scaled. From these the average deviation of the actual height of drop from the nominal is determined and this deviation, if significant, is applied as a correction to the nominal value of those higher drops which can not be scaled. The value of y for each drop is scaled and values of D, y, and y^2 recorded on a suitable card form. D is then plotted against y^2, as illustrated in Fig. 9. The elastic limit is located at the point preceding the one where the general trend of the points from the origin out begins to deviate definitely from a straight line. The value of d and values of H and Δ at the elastic limit are obtained as follows:

A straight line is drawn from the origin to that point not beyond the one selected as the elastic limit which gives the line of lowest slope (with respect to the horizontal axis). The corrected value of D is the intersection of this line with the vertical through the elastic limit point. Eq. 10 shows that d is one-half the slope of this line with respect to the *vertical* axis. H and Δ are then known from the fact that $H = D + y$, t' being neglected, and $\Delta = y + d$.

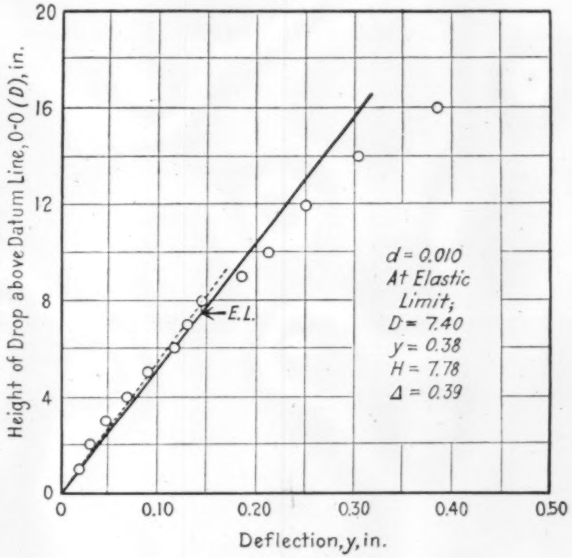

FIG. 9.—Typical Curve Showing D Plotted Against y^2.

Then for specimens of rectangular cross-section (whose width is b, height h, and span l),

Fiber stress at elastic limit, in pounds per square inch, $= \dfrac{3WHl}{\Delta b h^2}$ ......(11)

Modulus of elasticity, in pounds per square inch, $= \dfrac{WHl^3}{2\Delta^2 b h^3}$..........(12)

Elastic resilience, in inch-pounds per cubic inch, $= \dfrac{WH}{lbh}$........ ....(13)

IMPACT TESTS OF ROAD MATERIALS.

By Earl B. Smith.[1]

The application of impact methods of testing to such materials as brick, rock, gravel, concrete, asphalt, etc., has been only very general and not according to any standard or uniformity as to apparatus or methods except in a few specific instances. In nearly all cases, the attempt has been to determine the relative resistance of the material to shocks, it being the general conception that where shocks are to be sustained and resisted the desirable quality of the material should be toughness. The usual requirements for toughness are that the material shall not be fragile or easily shattered.

The machine which has been used in making impact tests at the U. S. Bureau of Public Roads, and elsewhere, on road materials has been the Page impact machine, as described in the Proceedings of this Society.[2] This machine consists essentially of a weight or hammer weighing 2 kg. which may be dropped vertically from any height up to about 150 cm. The specimen is placed on a supporting anvil (weighing 50 kg.) under an intervening plunger (weighing 1 kg.) on which the falling hammer strikes. This machine has been used principally in testing stone for road-building purposes and also for many special tests. The machine has been standardized by this Society in the Standard Method of Test for Toughness of Rock (Serial Designation: D 3 - 18),[3] which has been approved as a "Tentative American Standard" by the American Engineering Standards Committee. The test brings out the toughness quality in rock, which is the resistance offered to fracture by impact. Specimens for testing are obtained by means of core drillings, the final preparation of which results in a cylinder 25 mm. in height and approximately 25 mm. in diameter, the ends of the specimen being made plane and at right angles to the axis of the cylinder by means of grinding on an iron plate. The test consists of dropping the hammer 1 cm. for the first blow and for each succeeding blow from an additional height of 1 cm. until the specimen is broken. The height of the blow in centimeters which causes failure is the numerical value of the toughness of the specimen. These impact tests on rock are as reliable and indicative of quality as are other physical tests. This test has been used to show the relation between the toughness and the hardness of rock, and the results of this comparison[1] indicate that the average hardness of stone increases with the toughness.

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[1] Senior Testing Engineer, U. S. Bureau of Public Roads, Washington, D. C.

[2] *Proceedings*, Am. Soc. Test. Mats., Vol. VII, p. 601 (1907).

[3] 1921 Book of A.S.T.M. Standards, p. 711.

A larger machine of this type has been used for making tests on brick and concrete and for other special tests. In this larger machine, the falling hammer weighs 10 kg. instead of 2 kg. and the cast-iron anvil 500 kg. instead of 50 kg. as in the smaller machine. Impact tests have been made in this machine on brick. The brick is embedded edgewise in plaster of Paris and placed directly under the plunger of the testing machine. The hammer is raised and dropped from successive heights, increasing after each blow by 1 cm. until the brick is broken. The height of the fall of the last blow is taken to be the numerical result of the test, which is an indication of the relative toughness of the brick.

Tests have been made to determine the relative toughness of brick in comparison with the relative percentage of wear as determined in the standard brick rattler. There seems to be some definite relation between toughness as determined by the impact test and the percentage of wear as determined by the brick rattler, but this investigation has never been carried far enough to prove any definite relation or to warrant the substitution of the impact test for the rattler test. If this could be definitely established it would be a means of quickly and cheaply determining the relative qualities of paving bricks. It is possible that this might also be applied to stone paving block. Toughness as determined by the impact test seems to bear no definite relation to the crushing strength of brick or to the modulus of rupture as determined in the transverse test.

In the use of gravel in road construction it is desirable to know the relative toughness of the individual pieces, and it is also important to be able to determine the percentage of soft pieces in a certain lot of material. This is accomplished in a very definite way by the use of a new impact test, which consists in dropping a 2½-in. diameter steel ball on the piece of gravel supported on a suitable anvil. The height of drop depends upon the size of the piece being tested; and under the conditions of the test the test piece is satisfactory if it withstands a single blow without breaking or cracking. A detailed description of this apparatus and test is given by Mr. F. H. Jackson in a paper, "An Impact Test for Gravel," presented at this annual meeting.[2]

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[1] L. W. Page, "Relation between the Tests for the Wearing Qualities of Road-Building Rocks," *Proceedings*, Am. Soc. Test. Mats., Vol. XIII, p. 983 (1913). P. Hubbard and F. H. Jackson, *Journal of Agricultural Research*, Vol. V, February 7, 1916, p. 903.

[2] See p. 362.—ED.

Impact tests have been made on bituminous mixtures. It has been observed that this test in conjunction with a compression deformation test is a satisfactory method of determining the best proportion of a bitumen and an aggregate for road construction. It is for this reason that impact tests have been resorted to in an attempt to determine the toughness of different bituminous mixtures. Three types of machine have been used for this purpose. One type is the Page impact machine, using a 1-kg. hammer, the specimen being 1 in. in diameter and 1 in. in length. The test is to determine the minimum height of fall of the hammer which will cause rupture of the specimen. This test, made on a larger Page machine, is also used for bituminous concrete mixtures, the specimen being 3 in. in diameter and 3 in. high.

Another form of impact machine for testing bituminous materials is built on the pendulum principle and is described in the Proceedings of the Society.[1] The reading obtained is the amount of energy absorbed by the pendulum in separating two dies of special form cemented together with the bituminous material. Another machine using the same kind of dies for the test material and which is designed to accomplish the same purpose is described by W. H. Fulweiler.[2] This machine applies an impact tensile stress to two special dies cemented together with the bituminous material, the weight producing the impact being allowed to fall a distance of 6 in. before coming in contact with the link which separates the dies. These two machines give widely different results, even on the same material, but this may be expected from the character of the indicating devices and the methods of producing the impact. In the second of these machines the indicating device is an ordinary spring balance with a pointer for indicating the maximum movement of the spring. Such a device introduces into the impact system a cushioning effect which is entirely different from the effect produced by a pendulum striking a rigid projection on the two dies. The second machine can not be readily duplicated unless the spring balance used in the indicating device is exactly similar in every respect.

Impact tests on concrete have been made only to a very limited extent. No data seem to be at hand that would indicate any practical value of such tests. There have been, however, a number of tests made on road slabs by the U. S. Bureau of Public Roads.[3] These tests were made for the purpose of determining the actual strength or resistance of concrete slabs under the action of impact similar to that delivered by the wheels of a motor truck. The specimens tested were concrete slabs of varying thicknesses and 7 ft. square. The machine used in the tests consisted mainly of a frame work carrying a vertical plunger supported on a truck spring, the spring in turn carrying a heavy weight known as the sprung weight. The lower end of the plunger was shod with a section of a solid rubber tire. The test consisted in applying 500 blows at a drop of $\frac{1}{8}$ in., and then 500 blows at each additional $\frac{3}{8}$-in. drop until failure occurred by cracking or otherwise breaking the slab. These tests so far have served only to show the relative strength of different thicknesses of concrete slabs when supported on a clay subsoil. The series, however, is to be extended during the summer of 1922 on a large number of slabs and with an improved impact machine.

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[1] *Proceedings*, Am. Soc. Test. Mats., Vol. X, p. 595 (1910).

[2] *Good Roads*, February 3, 1912, p. 81.

[3] *Public Roads*, October, 1921.

Impact tests have also been made on a few other special materials, the most important of which are porcelain and terra cotta floor tile. A Page impact machine with a light hammer was used and the results indicate simply the comparative brittleness of different tile.

With the exception of the test on stone, there is no well-defined or standard method of procedure or a standard machine for making impact tests on the materials mentioned in this paper. Those tests which have been made are so varied and limited that no definite conclusions may be drawn as to their reliability, but they do seem to indicate that the impact testing of materials will determine certain qualities such as toughness and brittleness which can not be determined in any other way. Impact tests to be of service in design or in forming judgment as to the suitability of materials should be studied under an organized program by several different laboratories in order to determine the proper methods of procedure and the most suitable machine to use for this purpose. And such studies certainly should be made only after the fundamentals of impact forces and how they may be measured are thoroughly understood.

RESUMÉ OF AMERICAN PRACTICE IN NOTCHED BAR IMPACT TESTS OF METALS.

By C. L. Warwick.[1]

As an important feature of this Symposium on Impact Testing of Materials, it was determined to prepare a resumé of American practice in making the impact test on notched metal specimens. For this purpose a comprehensive questionnaire was sent from the headquarters of the Society to sixty-four testing engineers, laboratories, etc. Thirty-four replies were received. Eleven of those who replied stated they had no information on the subject; the remaining twenty-three gave considerable information regarding their practice in making the notched bar test, and the replies are appended in substantially complete form as received. These laboratories and individuals are listed below, and are identified by number in the appended statement of replies:

1. Watertown Arsenal, U. S. A.
2. U. S. Naval Engineering Experiment Station.
3. U. S. Bureau of Standards.
4. U. S. Naval Ordnance Plant.
5. U. S. Air Service.
6. Westinghouse Electric and Manufacturing Co.
7. Massachusetts Institute of Technology.
8. Pittsburgh Testing Laboratory.
9. New York Testing Laboratory.
10. Pierce Arrow Motor Car Co.
11. Crucible Steel Co., Research Dept.
12. Crucible Steel Co., Atha Works.
13. Halcomb Steel Co.
14. United Alloy Steel Corp.
15. Midvale Steel and Ordnance Co.
16. Dow Chemical Co.
17. General Electric Co.
18. Henry Souther Engineering Corp.
19. University of Wisconsin.
20. International Nickel Co.
21. Carpenter Steel Co.
22. Albert Sauveur, Professor of Metallurgy, Harvard University.
23. General Motors Research Corp.

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[1] Secretary-Treasurer, American Society for Testing Materials, Philadelphia.

It should be explained that Question 1 contained six sub-divisions in which was requested detail information regarding machines and specimens, and the information thus furnished has been assembled in Table I and Figs. 1 to 5, inclusive.

A brief summary will be given of the replies to some of these questions.

Types of Impact Machines in Use.—In answer to Question 1, inquiring what type or types of impact machines are customarily used for the notched bar impact tests, it developed that the Charpy pendulum machine is so used in eleven of the twenty-three laboratories, the Izod pendulum machine in thirteen laboratories, the Olsen, Russell and Dow pendulum machines each in one laboratory, and the Guillery rotating flywheel machine in one laboratory. The Stanton repeated impact machine is used in four laboratories. In addition, one of the laboratories that does considerable research on impact testing (Watertown Arsenal) uses a Fremont drop-hammer machine, a Guillery machine, a Matsumura repeated impact testing machine and a quadruple hammer repeated impact testing machine.

Test Specimens.—Very complete data regarding form and dimensions of test specimens in every-day use are given in Table I and Figs. 1 to 5, inclusive.

All eleven laboratories using the Charpy machine have adopted the 0.394-in. (10-mm.) square specimen, 2.165 in. (55 mm.) in length. Eight laboratories use the "round" notch, two the "V" notch with rounded bottom, and one laboratory uses both forms. In the case of the round notch a uniform depth of 0.197 in. (5 mm.) is used. Two widths of notch are in use, 0.039 in. (1 mm.) in six laboratories and 0.079 in. (2 mm.) in two laboratories. The radius of the bottom of the notch also varies, as indicated in Fig. 1 (*a*). One laboratory uses a drilled notch, with the sides flared out to an angle of 90 deg., as shown in Fig. 1 (*a*). The three laboratories using the V notch have uniform requirements, the notch having an angle of 45 deg., a depth of 0.079 in. (2 mm.), with the radius at the bottom of the notch 0.01 in. (0.25 mm.). See Fig. 1 (*b*).[1]

No laboratories have reported the use of round Charpy specimens.

In the case of the Izod test, both round and square specimens are used. In two laboratories the square specimens have a round notch, as shown in Fig. 2 (*a*). In nine laboratories the square specimen is used with a V notch, usually of the same dimensions as mentioned above for the Charpy specimens.[1] Two laboratories report the use of specimens rectangular in cross-section, in each case the notch having an angle of 90 instead of 45 deg. Details are given in Fig. 2 (*b*).

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[1] This is the same as the British standard, referred to in the papers by D. J. McAdam and T. D. Lynch in this Symposium. See pp. 47 and 100 ff.

Five laboratories report the use of the round Izod specimen, in each case with the V notch. The diameter of the specimen is uniformly 0.45 in.; the notch has an angle of 45 deg. and a depth of 0.13 in.[1]

All laboratories reporting the use of the V notch round the bottom of the notch with a radius of 0.01 in.

Thus it will be seen that in so far as this questionnaire is at all indicative, the square Charpy specimen with the round notch seems to be more widely used than with the V notch, whereas the square Izod specimen with the rounded V notch seems to be more widely used. These results are interesting in view of the latest recommendations of the British Engineering Standards Association, reported elsewhere in this Symposium,[2] that square or rectangular specimens should be used with a rounded V notch.

The specimens for the Olsen, Dow, Guillery and Russell machines are all square in cross-section with a round notch. The specimen used in the Fremont machine is illustrated in Fig. 3. The specimen used in the Stanton repeated impact machine is illustrated in Fig. 4.

Six laboratories reported that they make impact tests in tension, using the Charpy machine as adapted for tension tests. Typical notched and unnotched tension specimens are shown in Fig. 5.

GENERAL DISCUSSION.

While a study in detail of the replies to the questionnaire has been deferred, some features that stand out rather definitely may be mentioned. In answer to Question 3, "What faults or differences do you find in the machines with which you have had experience?" it is brought out that one of the chief faults of all impact machines is the difficulty of measuring accurately the work expended in the rupture of the specimen. Several laboratories point out that the tests at present made are not especially adaptable to ductile materials. One laboratory states that although there are no faults as to operation or accuracy, the results obtained are in units inapplicable to the problems at issue.

In discussing the comparability of results obtained from the different types of impact machines, the opinion is rather general that these results cannot be very satisfactorily compared, two laboratories that have had considerable experience making the statement that they have been unable to find any relation between Charpy and Izod test values. Several laboratories, however, point out that while results may not be strictly comparable in an absolute sense, they may be compared in a relative sense with some degree of success.

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[1] This is the so-called Philpot specimen, referred to in the paper by D. J. McAdam in this Symposium. See p. 48.

[2] See pp. 102, 103.

Eighteen laboratories answered Question 6, "Have you found any type of machine to be better adapted for comparison of test material which is generally of a tough nature than material which has a wide range of brittleness or the reverse?" More than half were not prepared to express any definite opinion, and in so far as definite opinions were expressed, four laboratories indicated a preference for the Charpy, two for the Stanton, one for the Izod and one for the Dow.

In discussing Question 8, "Have you any opinion as to the relative importance of transverse and tension impact tests?" several laboratories expressed the view that tension impact testing should be given more attention, one laboratory expressing the view that since the tension impact test is a "simple stress" test there is a greater probability of our being able to relate the results to static test properties. One laboratory suggested that the impact tension test should be more largely used for ductile materials. Another laboratory believes that the tension impact test may prove superior to the transverse test. On the other hand, four laboratories make the definite statement that in their opinion the transverse impact test is better than the tension impact test.

The answers to Question 9 show that on the whole a wide range of ferrous and non-ferrous metals are being subjected to the notched impact test. Ten laboratories have reported that they use the same specimen for the ferrous and non-ferrous metals.

There seem to be very few data upon which to base an opinion as to the relation of impact tests on ferrous and non-ferrous metals and on metallic and non-metallic materials.

Question 11, "In what particular line do you consider impact tests to be of the most use, and do you think that the test is susceptible of standardization for particular rather than general application?" brought out some interesting replies. The answers to the first part of the question include the following: That impact tests are particularly valuable where it is desired to determine degrees of toughness of metals by heat-treating processes; as a check on specified heat treatment for carbon and alloy steels; as a substitute for static transverse tests to disclose impairment of ductility; in the study of causes of failure; in the study of materials subject to shock under serious conditions.

As to the possibility of standardizing tests for particular rather than general application, the consensus of opinion in so far as this question was answered would seem to be that it might be possible in the present state of the art to standardize the impact test for application to particular problems, but not for general application. Several investigators point out that, at present, experience is not sufficiently extensive to warrant an attempt at a general standardization of the impact test.

One of the objects of the questionnaire was to obtain information that would be of aid to any committee of the Society which might be charged with the further investigation and possible standardization of methods of impact testing. The replies to Question 12, "Are you in favor of the American Society for Testing Materials attempting the standardization of impact testing at this time?" are therefore of interest. Twenty of the twenty-three laboratories answered this question, fourteen in the affirmative and six in the negative. Of the latter, one laboratory pointed out that complete standardization at the present time would retard a vast amount of experimental work. Several of those who replied in the affirmative made the comment that it is desirable that American standards should be established and that this work should be undertaken by the Society. Regarding the inquiry as to whether a single machine should be standardized, there were eleven affirmative and five negative replies. A number who replied to this question pointed out that further study may make it necessary to standardize both the beam type and cantilever type machines. A number have pointed out the advantage of using the same specimen for several standard machines, but see difficulties in securing the adoption of a single standard. One laboratory points out the difficulty of drilling round notches in some of the heat-treated steels.

In conclusion, the writer believes that the results of this questionnaire point to the desirability of the American Society for Testing Materials undertaking a suitable study of impact testing, to the end that methods of impact testing shall be prepared that will compare with our methods for tension, compression and other tests of materials. It is hoped that this Symposium and the discussion of the papers presented will emphasize very definitely the desirability of our Society taking up this work.

The committee wishes to express its appreciation of the cooperation of all who have answered this questionnaire, which has made possible what is thought to be a very complete resumé of American practice.

APPENDIX.

RETURNS FROM QUESTIONNAIRE ON NOTCHED BAR IMPACT TESTS OF METALS[1]

1. *What type of impact machine do you customarily use for notched bar impact tests (both single blow and repeated) and have you reasons for giving it preference?*

1. Charpy pendulum machine of 217 ft-lb. (30 kgm.) capacity, for routine tests and general work. Our reasons for preference are: (1) Regular and consistent results obtained; (2) suitability for testing material of a wide range of toughness; (3) ease and rapidity of operation; and (4) simplicity and comparative cheapness of test specimen. Other impact testing machines, for both single-blow and repeated-blow tests, are in use at this laboratory for research work (see Table).
2. Charpy (American made).
3. Single blow: Charpy and Izod. Repeated blow: Eden-Foster. Charpy preferred; better fracture for ductile materials, more freedom from direct shearing effects on account of lack of restraint in method of holding specimen.
4. Charpy type (American made) used because most of the data available to us of tests on similar material were of Charpy tests.
5. In the light of some recent tests, we are inclined to favor the Charpy machine with the V notched specimen because we find it gives higher results. These conclusions are drawn from a number of tests on heat-treated alloy steels using both Izod and Charpy machines with square specimens having round notches and V notches.
6. Izod (American made).
7. Charpy (American made). This machine was used during the war in the United States, Great Britain and France.
8. Izod. Purchased to make tests for British Government.
9. Olsen.
10. Izod, 23 ft-lb., single blow; also Stanton, repeated-blow fatigue testing machine.
11. Izod (American made).
12. Charpy.
13. Izod and Stanton.
14. Izod.
15. Charpy and Izod.
16. Dow single-blow impact testing machine. Reasons for preference are: Simplicity and ease of operation; simplicity and ease of machining specimen; range admirably adapted to light alloys.
17. Charpy (American made).
18. Izod. Believe Stanton repeated-impact machine desirable, but do not own one.
19. Russell pendulum machine, single blow.
20. Charpy (American made) and Izod (American made).
21. Guillery machine, single blow.
22. Charpy.
23. Izod. Pendulum type preferable because of economy and ease of operation

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[1] The numbers 1 to 23 refer to the laboratory numbers given on p. 78.

TABLE I.—SUMMARY OF DATA ON MACHINES AND TEST SPECIMENS FOR NOTCHED BAR IMPACT TESTS OF METALS.

The data in Columns 6–15, inclusive, refer to specimens for transverse impact tests. Data concerning specimens for tension impact tests are given in footnotes.

Laboratory No.	Impact Machine.				Details of Test Specimens.													Laboratory No.
						Dimensions.												
								Notch.										
	Type of Machine.	Capacity, ft-lb.	Weight of Pendulum, lb.	Height of Fall, ft.	Type, Round or Square	Length, in.	Side or Diameter, in.	Type.	Depth, in.	Width, in.	Radius at Bottom, in.	Included Angle, V type, deg.	Span between Supports (Beam Type), in.	Striking Distance (Cantilever Type), in.	Method of Finishing Specimen.	Method of Cutting Notch.	Method of Checking Notch Radius.	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1[a]	Charpy[1]	217	49.91	4.39	Square	2.165	0.394	Round	0.197	0.039	0.026	....	1.575	....	Planed or milled; then ground	Milled	Radius obtained from tool used	1
	Charpy[1]	2170	212.45	10.35	Square	6.102	1.181	Round	0.591	0.158	0.079	....	4.72	....				
	Izod	120	60	2	Square	2.5	0.394	V	0.079	....	0.01	45	....	0.866				
					Round	3	0.45	V	0.13	....	0.01	45	....	0.866				
	Guillery (Rotating Hammer)	1989	....	....	Same specimen as for 2170 ft-lb. Charpy													
	Fremont (Drop Hammer)	29 (approx.) 43 (approx.)	....	Up to 13	Rect.	1.181	0.315 by 0.394	Rect.	0.039	0.039	....	....	....	....				
	Mouton Universel de 200 kgm. (Drop Hammer)	....	Variable	Up to 13	Will test any type of specimen													
	Stanton (Repeated Impact)	....	....	Variable	Round	7	0.5	V	0.05	....	0.02	60	....	....				
2	Charpy Impact	224.5	50.97	4.41	Square	2.165±0.05	0.394±0.0005	Round	0.197	0.039	0.0197	....	1.575	....	Milling machine and shaper	Drilled and cut	By size of drill	2
	Shear	100	33.33	3	Rect.	3	0.25 by 0.375	Unnotched					....	Shear				
3	Charpy	224.1	50.81	4.78	Square	2.1	0.394±0.001	V	0.079	....	0.01	45	1.575	....	Milled and ground	Milled with special cutter and lapped with wire of radius of finished fillet	Not checked beyond lapping operation	3
	Izod	120	83.53	2.41	Square	2.953	0.394±0.001	V	0.079	....	0.01	45	....	0.875				
					Round	2.953	0.45 ±0.001	V	0.13	....	0.01	45	....	0.875				
4	Charpy	235	49.2	4.78	Square	2.1±0.05	0.394±0.001	Round	0.197	....	0.055	90	1.575	....	Ground	Drilled	By micrometer and wire method	4

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
5	Charpy	225	50.882	4.423	Square	2.16±0.005	0.394±0.003	Round V	0.197 0.079	0.079	0.039 0.01	 45	1.575	....	Milled and ground	Round notches drilled when not too hard; otherwise milled. V notches all milled	Check milling cutter or drill	5
	Charpy	23	5.203	4.196	Same specimen as for 225 ft-lb. Charpy													
	Izod	120	70 (approx.)	1.9 (approx.)	Square	2.95±0.005	0.394±0.003	Round V	0.197 0.079	0.079	0.039 0.01	 45	.....	0.866				
	Stanton (Repeated Impact)	....	5.5 (Hammer)	Up to 3.5 in.	Round	6.75	0.5	V	0.038	0.055	0.01	60	....	....				
6	Izod	120	....	2.09	Square	2.95+0.08	0.394±0.001	V	0.079	....	0.01	45	....	0.870	Milled and ground	Special milling cutter	By gage	6
7	Charpy[2]	225 (approx.)	51 (approx.)	4.1 (approx.)	Square	2.165	0.394	Round	0.197	0.039	0.02 (approx.)	....	1.575	....	Any method if true	Milled	Little difference noted if cutters operate properly	7
8	Izod	120	48	2.5	Square	3±0.1	0.394±0.003	V	0.079	....	0.01	45	....	0.866	Milled and ground	Milled	Special cutter checked	8
9	Olsen	100	33.33	3	Square	1.575±0.002	0.394±0.001	Round	0.197	0.079	0.039	....	....	0.394	Milled	Machined	.....	9
10	Izod	23	....	....	Rect.	2	0.1875 by 0.375 ±0.002	V	0.05	....	0.02	90	....	0.75	Milled	Machined	By gage	10
	Stanton (Repeated Impact)	....	5.25 (Hammer)	½, 1 and 2 in.	Round	....	0.5±0.002	V	0.05	....	0.02	90	4.5	....	Ground	....	.....	
11	Izod	100	....	3.5	Square	2	0.394	Round	0.197	0.039	0.0197	....	....	1.0	Shaped or ground	With carborundum wheel	.....	11
12	Charpy	217	45.28	4.375	Square	2.205±0.0005	0.394±0.0005	Round	0.197	0.079	0.039	....	1.575	....	Ground	Machined	By gage	12
13	Izod	120	....	....	Round[3]	5.125	0.450±0.001	V	0.130	....	0.01	45	....	0.813	Ground	Milled	By microscopic examination of cutter	13
	Stanton (Repeated Impact)	....	....	Up to 3.5 in.	Round	6.5	0.500±0.001	Round	0.05	0.05	0.01	....	4.5	....	Ground	Turned	.....	
14	Izod	120	....	3.5	Square	2.953+0.079	0.394±0.001	V	0.079	....	0.01	45	....	0.866	Milled	Milled	By template	14

[a] This laboratory also has two other types of machines: (1) A Matsumura Repeated Impact Testing Machine, in which the fall of hammer and speed can be varied. The specimens may be either round or square and are rotated 180 deg. between impacts. (2) A Quadruple Hammer Repeated Impact Testing Machine, in which the weights of the hammers can be varied. The specimen which is 0.472 in. in diameter and 7.1 in. long, is struck blows on each side diametrically opposite.

[1] This laboratory uses the two Charpy machines to test round specimens (both notched and unnotched) in tension. The specimens for the 217 ft.-lb. machine are illustrated in Fig. 5.

[2] This laboratory uses the Charpy machine to test round notched specimens in tension.

[3] Both round and square specimens are used, but former are preferred.

TABLE I.—SUMMARY OF DATA ON MACHINES AND TEST SPECIMENS FOR NOTCHED BAR IMPACT TESTS FOR METALS.—*Continued.*

The data in Columns 6–15, inclusive, refer to specimens for transverse impact tests. **Data concerning specimens for tension impact tests are given in footnotes.**

Laboratory No.	Impact Machine.				Details of Test Specimens.													Laboratory No.
					Dimensions													
								Notch.										
	Type of Machine.	Capacity, ft-lb.	Weight of Pendulum, lb.	Height of Fall, ft.	Type, Round or Square.	Length, in.	Side or Diameter, in.	Type.	Depth, in.	Width, in.	Radius at Bottom, in.	Included Angle, V type, deg.	Span between Supports (Beam Type), in.	Striking Distance (Cantilever Type), in.	Method of Finishing Specimen.	Method of Cutting Notch.	Method of Checking Notch Radius.	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
15	Charpy	216.5	49.68	4.356	Square	2.165±0.039	0.391±0.001	Round	0.197	0.039	0.0197	....	1.575	....	Ground	Ground	By measurement	15
	Izod	36	24	1.5	Rect.	2.125	0.1875 by 0.375 0.5±0.01	V	0.05	....	....	90	....	0.375	Machined	Machined	By template	
16	Dow	14	7	2	Square	4±0.5	±0.001	Round	0.125	0.125	0.0625	....	....	0.50	Tested as cast	Milled	Not checked; same tool used exclusively	16
17	Charpy[4]	226.3	51.068	4.433	Square	2.165±0.01	0.391±0.001	Round	0.197	0.039	0.0197	....	1.562	....	Ground	Milled	By template	17
18	Izod	120	60	2	Round	3±0.005	0.450±0.001	V	0.130	....	0.01	45	....	0.866	Filed	Machined	By template	18
19	Russell	600	185	up to 3.25	Square	4±0.01	0.375±0.001	Round	0.187	0.079	0.039	....	2.5	....	Milled	Drilled	.....	19
20	Charpy	224	50.64	4.421	Square	2.1±0.015	0.394±0.004	V	0.079	....	0.01	45	1.575	....	Ground	Machined	On cutter	20
	Izod	120	....	....	Square	2.953±0.015	0.394±0.004	V	0.079	....	0.01	45	....	0.866	Ground	Machined	On cutter	
21	Guillery	433	....	....	Square	2.312	0.375	Round	0.0625	0.125	0.0625	....	1.75	....	Ground	Milled	Radius is permanent on cutters	21
22	Charpy[5]	225	51 (approx.)	4.4 (approx.)	Square	2.165±0.015	0.394±0.0005	Round	0.197	0.039	0.0197	....	1.562	....	Shaper	Milled	By space bar in slot	22
23	Izod	120	60	2	Round	2.85−0.030	0.450±0.001	V	0.122	....	0.01	45	....	0.866	Ground	Machined	By gage	23

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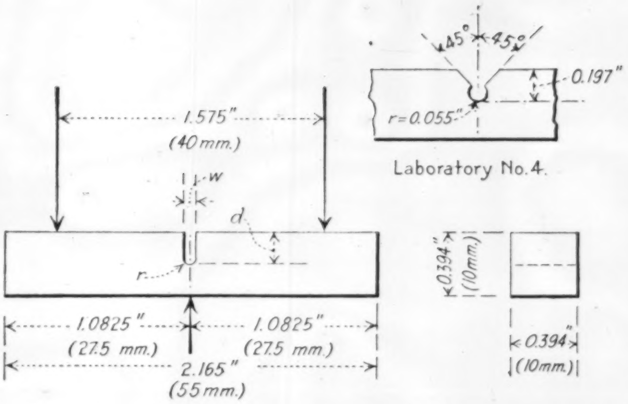
[4] **This laboratory uses the Charpy machine to test round specimens (both notched and unnotched) in tension. The specimens are the same as those illustrated in Fig. 5.**

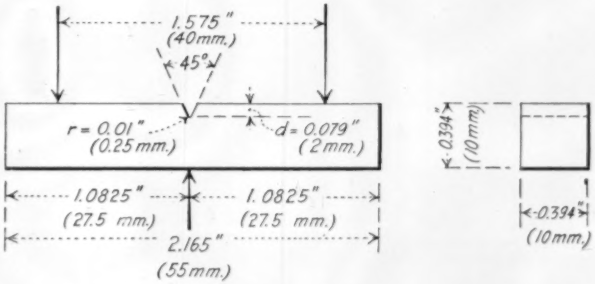
[5] **This laboratory uses the Charpy machine to test round specimens in tension.**


45°
45°
0.197"
r=0.055"
Laboratory No. 4.
1.575"
(40 mm.)
w
d
r
0.394"
(10 mm.)
1.0825"
(27.5 mm.)
1.0825"
(27.5 mm.)
2.165"
(55 mm.)
0.394"
(10 mm.)

Laboratory No.	Dimensions of Notch.		
	Depth, *d*.	Width, *w*.	Radius, *r*.
2, 7, 15, 17, 22	0.197" (5 mm.)	0.039" (1 mm.)	0.0197" (0.5 mm.)
1	"	"	0.026" (0.66 mm.)
5, 12	"	0.079" (2 mm.)	0.039" (1 mm.)

All nine Laboratories agree as to Width of Specimen, and substantially as to Length and Span between Supports.

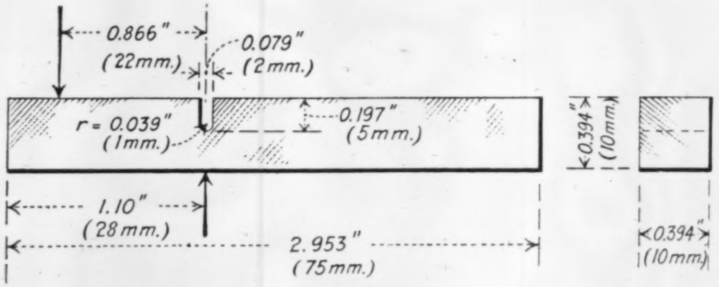
(a) Square Specimen, Round Notch.


1.575"
(40 mm.)
45°
r = 0.01"
(0.25 mm.)
d = 0.079"
(2 mm.)
0.394"
(10 mm.)
1.0825"
(27.5 mm.)
1.0825"
(27.5 mm.)
2.165"
(55 mm.)
0.394"
(10 mm.)

Used by Laboratories No. 3, 5 and 20.

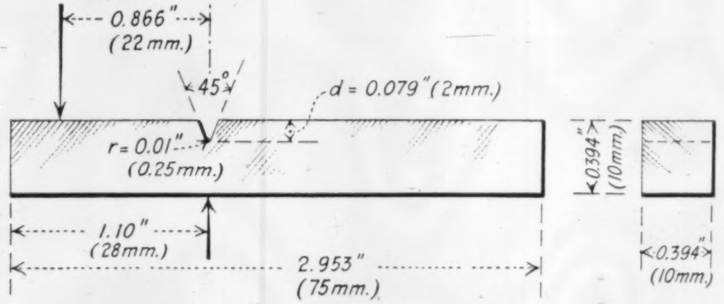
(b) Square Specimen, V Notch.

FIG. 1.—Typical Charpy Transverse Test Specimens


0.866"
(22mm.)
0.079"
(2mm.)
r = 0.039"
(1mm.)
0.197"
(5mm.)
0.394"
(10mm.)
1.10"
(28mm.)
2.953"
(75mm.)
0.394"
(10mm.)

Standard of Lab. No. 5 as illustrated. Lab. No. 11 uses Same Specimen (substantially) except Notch is only half as wide, 0.039" (1mm.)

(a) Square Specimen, Round Notch.

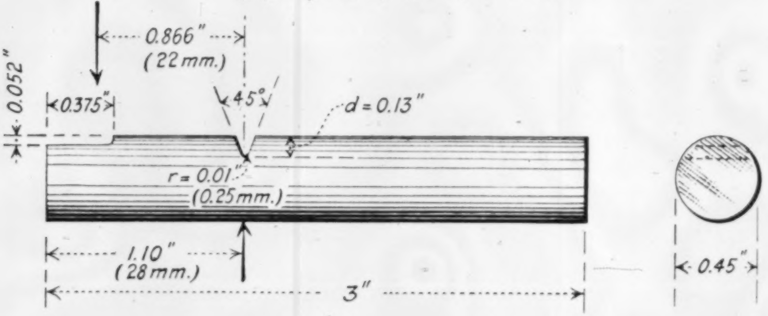

0.866"
(22mm.)
45°
d = 0.079" (2mm.)
r = 0.01"
(0.25mm.)
0.394"
(10mm.)
1.10"
(28mm.)
2.953"
(75mm.)
0.394"
(10mm.)

Standard of Labs. Nos: 1, 3, 5, 6, 8, 14 and 20.

Labs. Nos. 10 and 15 use Rectangular Specimens $\frac{3}{16}$" x $\frac{3}{8}$", notched 0.05" deep, included Angle 90°, Radius at Bottom 0.02".

There are Minor Differences in Lengths and Striking Distances. See Table.

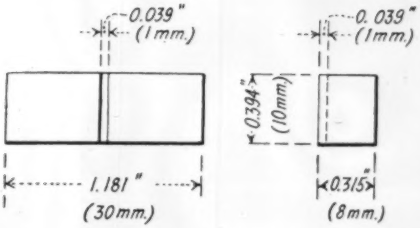
(b) Square Specimen, V Notch.


0.866"
(22mm.)
0.052"
0.375"
45°
d = 0.13"
r = 0.01"
(0.25mm.)
1.10"
(28mm.)
3"
0.45"

Standard of Labs. Nos. 1, 3, 13, 18, 23; except No. 23 uses d = 0.122".
There are Minor Variations in Lengths and Striking Distances. See Table.

(c) Round Specimen, V Notch.

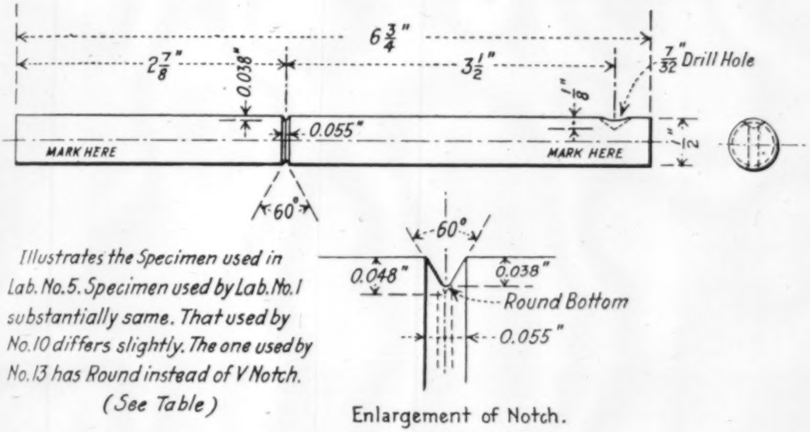
FIG. 2.—Typical Izod Transverse Test Specimens.



0.039"
(1mm.)
0.039"
(1mm.)
0.394"
(10mm.)
1.181"
(30mm.)
0.315"
(8mm.)

FIG. 3.—Test Specimen for Fremont Impact Machine.

Specimen in use at Laboratory No. 1. See Table.

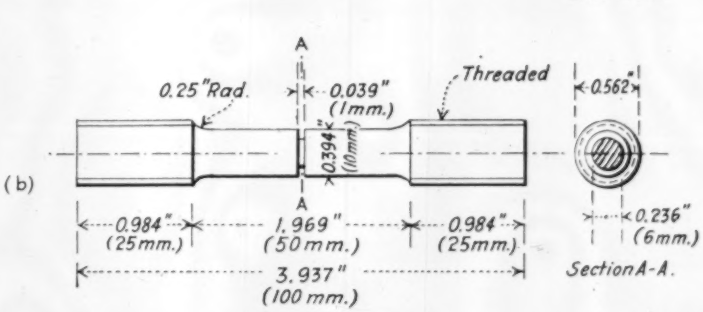


6 3/4"
2 7/8"
3 1/2"
0.038"
1/8"
7/32" Drill Hole
0.055"
1/2"
MARK HERE
MARK HERE
60°
60°
0.048"
0.038"
Round Bottom
0.055"

Illustrates the Specimen used in Lab. No. 5. Specimen used by Lab. No. 1 substantially same. That used by No. 10 differs slightly. The one used by No. 13 has Round instead of V Notch. (See Table)

Enlargement of Notch.

FIG. 4.—Typical Stanton Repeated Impact Test Specimen.



0.125" Rad.
Gage
2"
Threaded
0.236"
(6mm.)
(a)
0.818"
0.818"
0.562"
3.937"
(100 mm.)
End View.
A
0.25" Rad.
0.039"
(1mm.)
Threaded
0.562"
0.394"
(10mm.)
(b)
A
0.984"
(25mm.)
1.969"
(50mm.)
0.984"
(25mm.)
0.236"
(6mm.)
3.937"
(100 mm.)
Section A-A.

FIG. 5.—Charpy Tension Test Specimens: (*a*) Unnotched; (*b*) Notched.

Specimens in use at Laboratory No. 1 for 217 ft-lb. Charpy machine and at Laboratory No. 17.

2. *Do you use a jig for setting the specimen in the machine?*

1. No. (Not in small machine used for routine tests. A jig is used in large machines.)
2. No.
3. Yes.
4. No.
5. Yes.
6. Yes.
7. No.
8. Yes.
9. No.
10. Yes.
11. No.
12. Yes.
13. Yes.
14. (No comments.)
15. Template, Charpy; jigs, Izod.
16. Yes.
17. Yes.
18. Yes.
19. Yes.
20. Yes.
21. No.
22. No.
23. Yes.

3. *What faults or differences do you find in the machines with which you have had experience?*

1. (*a*) The chief fault of all impact machines is the failure of means for distinguishing accurately the work expended in rupture of the specimen from the work expended in producing vibrations, friction, etc.
    (*b*) In the case of less brittle material, the work expended in overcoming friction of the specimen is greater than in cases where more brittle material is tested.
    (*c*) The method of determining the residual energy in the Fremont machine has not proved reliable.
2. (No comments.)
3. None of them are especially adaptable to ductile materials with present standard notches. Do not cause full rupture. Charpy better than Izod. Do not permit of determination of amount of energy absorbed by anvil and present machines are so light in base weight that extra anchorage is necessary to keep machine in place.
4. No faults as to operation or accuracy. Results are obtained in units inapplicable to problems at issue. It is necessary to make too many unproved suppositions in interpreting the results.
5. In all cases where the specimen bends but does not break, the results, of course, are not truly comparable. This is probably more serious in the case of the Charpy machine because the specimen is doubled up and drawn through the slot between the support anvils, thus greatly retarding the rise of the hammer.

6. Specimens of large size, say 1 in. square, are being used in our Izod machine for weaker materials as fiber, micarta, etc., but are not entirely satisfactory because the distance between vise and striking edge is too short and is not adjustable. With the large samples in this machine, the results are probably largely influenced by shear.
7. We have used only the Charpy machine in our laboratory. The faults in this one and others that have come under my attention are very numerous. We feel that the Charpy is the most satisfactory as yet. Improvements are very possible in this.
8. Satisfactory for comparing any one material.
9. No particular faults with the machines themselves.
10. We would prefer the larger Izod machine; the specimen we use for our 23 ft-lb. Izod machine is rather small. We would like to be able to use a ½-in. round specimen for the single blow test. We like the Stanton machine.
11. The Izod is a fairly satisfactory machine.
12. Only one machine (Charpy) used. Find little or no fault if test pieces are carefully prepared, or machine in good order.
13. (No comments.)
14. (No comments.)
15. Difficult to make Charpy specimen. On low values the difference between determinations is so small that readings are indeterminate. Errors of machining. Concordant results are not always obtained.
16. When one full series of magnesium alloys was tested on both the Charpy and Dow machine, the Charpy results on the whole series fell within too narrow a range while poor checks were obtained on the specimens of the individual alloys, as compared with the Dow machine.
17. No experience.
18. (No comments.)
19. (No comments.)
20. See answer to Question 6.
21. The Guillery machine has been used for fifteen years with consistent and satisfactory results. Tests are run in quadruplicate.
22. (No comments.)
23. The single blow machine, such as the Izod, is rapid and easy to operate and the test specimens are small and comparatively inexpensive. This is not true of most of the other types.

4. *What is your opinion as to the comparability of results obtained from different types of impact machines?*

1. In our opinion the comparability of results obtained on different types of machines is not very satisfactory in an absolute sense, although in a parallel sense the comparability is better.
2. (No comments.)
3. Our tests indicate that it is possible to make a round and square Izod specimen that will give similar results. Charpy not well adapted for round specimens. Do not find relation between Charpy and Izod machines that is consistent.
4. (No comments.)
5. I have not been able to find any definite relation between Charpy and Izod test values.

6. We have had very little experience in comparing results obtained by various machines, but can see no reason why results should not be comparative if tests are relative.
7. Charpy machines of the same capacity will give comparable results if great care is used in fabricating specimens. Machines of different capacity will not check quantitatively.
8. I do not know enough about machines other than the Izod to give an opinion.
9. No results from different types of machines are directly comparable. A relationship can be established, however.
10. Not easy to get good comparisons.
11. No data.
12. No personal experience.
13. Actual readings in foot-pounds not comparable. Characteristics of material in curves have same general shape.
14. (No comments.)
15. Difficult to answer. Comparison fair between some types of machines, while comparison with other types show large discrepancies. We have obtained the greatest discrepancy between Izod type machine and Fremont machine.
16. Our only experience is that quoted above under Question 3. In this instance the Charpy values were practically meaningless.
17. No experience.
18. Consider Charpy more sensitive than Izod.
19. Literature indicates considerable divergence. No experience.
20. (No comments.)
21. Limited experience indicates tests are not comparable.
22. My experience is confined to the use of the Charpy machine.
23. Results are fairly consistent with the various types.

5. *Are you of the opinion that there are important comparative differences between the use of large-capacity impact machines and large specimens and small-capacity impact machines and small specimens?*

1. In our opinion there are important comparative differences in the use of large-capacity machines with large specimens and small-capacity machines and small specimens. The large-capacity machine is to be preferred as minimizing the irregularities due to heterogeneity, flaws, etc., although the expense of test specimens is naturally greater.
2. (No comments.)
3. Our experience would not properly allow statement on this. We believe it should be investigated thoroughly, however, as it will be found necessary to standardize a smaller and larger specimen as well as what might be considered the particular standard specimen.
4. (No comments.)
5. In order to test light alloys we have a Charpy hammer weighing one-tenth of the standard hammer. Comparative tests made on steels using both hammers show very little difference in impact value. At one time we made Izod and Charpy tests on specimens of different cross-sectional areas in order to determine whether the impact values bore any relation to the area. Although the results were somewhat irregular there was a definite tendency for the impact value to vary with the area behind the notch. Tests were made on S. A. E. 1020 and 1040 steel.

6. Our experience with the large-capacity machine and large specimen has been discouraging as explained before. In general, we believe the small machine and small sample would be preferable, although we have never tried it.
7. We have no large machine, but it seems from tests that have come to notice that the large and small machines class steel specimens in about the same way.
8. (No comments.)
9. (No comments.)
10. Our small Izod machine (23 ft-lb.) gives a fairly good comparison with the large Izod (120 ft-lb.).
11. Large machine gives better average figures.
12. No personal experience, but should say that there are likely to be differences.
13. One difference is that in a large machine the specimen is larger, hence actually more of the steel is tested than when a small specimen is used.
14. (No comments.)
15. Do not know.
16. No information to give on this subject.
17. No experience.
18. (No comments.)
19. Yes.
20. (No comments.)
21. No experience.
22. Cannot express an opinion.
23. No.

6. *Have you found any type of machine to be better adapted for comparison of test material which is generally of a tough nature than material which has a wide range of brittleness or the reverse?*

1. The Charpy pendulum machine is in our opinion better adapted for testing material of a general tough nature than other types of machines.
2. (No comments.)
3. Charpy. See answer to Question 1.
4. (No comments.)
5. Have found nothing definite.
6. (No comments.)
7. We have not had sufficient experience with different types of machines to answer definitely. My answer would be that the Charpy seems to offer the best solution at present.
8. No.
9. No.
10. No.
11. No data.
12. No experience.
13. For comparison of brittle material, I think the Stanton is better because by suitably decreasing the energy of blow long enough runs can be obtained. On the Izod the energy absorbed in breaking a real brittle piece is too small to give comparisons.
14. (No comments.)

15. Both the Charpy and Izod machines show poor comparisons on brittle material, while on tough material results are comparative.
16. No comparative data to offer in addition to that already given. The Dow machine was designed and built primarily for the toughness range encountered in light alloys.
17. No experience.
18. Stanton machine will give a wider range of measurement and enable one to differentiate closer in some instances.
19. (No comments.)
20. The Charpy machine appears more satisfactory for tough material as a greater bend is obtained with less drag on the pendulum with those materials that do not break completely.
21. No experience.
22. No experience.
23. No.

7. *Do you make tension impact tests? What are the dimensions of the test specimen used? Give any further details regarding this test.*

1. Yes. See sketches submitted.[1] Tension tests are made at this laboratory on both the large and small Charpy machine using notched and unnotched test bars. Tension tests can be made on the "Mouton Universel" drop hammer machine, but the Izod, Fremont and Guillery machines are not equipped for tension tests.
2. (No comments.)
3. Not regularly. One suggested by Henry Souther Engineering Co.
4. No.
5. Very few.
6. No.
7. Yes. Regular Charpy tension specimens with the standard notch. The sides of the notch need not be parallel.
8. No.
9. No.
10. No.
11. No.
12. No.
13. No.
14. No.
15. We have made tension tests, but it is not our practice. Standard Charpy tension specimens.
16. No.
17. Yes. See sketches submitted.[2]
18. No.
19. No.
20. (No comments.)
21. No.
22. Yes.
23. No.

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[1] Specimens for 217-ft-lb. Charpy machine illustrated in Fig. 5.

[2] Specimens same as illustrated in Fig. 5.

8. *Have you any opinion as to the relative importance of transverse and tension impact tests?*

1. At the present time this laboratory has no definite opinion, but believes that the tension impact test may prove superior to the transverse test.
2. (No comments.)
3. Believe impact tension test should be more largely used for ductile materials, as such a test is more likely to give a complete impact failure free from specimen-holding device and frictional effects.
4. Study of the literature of the subject has led me to attribute discrepancies between impact and static tests to the notching, and not to the circumstance that the power was applied by a blow instead of by slow action, in the class of steels studied by us. Notched bars show transverse weakness.
5. It seems to me that the development of the tension impact test should be given more attention because it is a simple stress test and in the end we are more likely to be able to connect the results with other physical properties.
6. No.
7. We feel that the transverse test gives more uniform results. We do not wish to go on record just at present with regard to this matter. The transverse specimen is much easier to fabricate.
8. No.
9. No.
10. Believe the transverse notched test the better.
11. (No comments.)
12. (No comments.)
13. In general I would think the transverse test would be the more sensitive to detection of brittleness from defective material.
14. (No comments.)
15. (No comments.)
16. Have had no experience with impact tension.
17. Have not had sufficient experience to warrant any definite opinion.
18. No.
19. (No comments.)
20. (No comments.)
21. No.
22. (No comments.)
23. In my opinion, the transverse test is the more logical of the two. The tension impact test requires a more elaborate machine and specimen and gives the same results.

9. *What metals are you testing in impact?* (*a*) *Do you use the same specimens for ferrous and non-ferrous metals?*

1. Carbon and alloy steels. Non-ferrous metals have not commonly been tested at this laboratory.
2. Carbon and alloy steels and non-ferrous metals. (*a*) Yes.
3. Steels principally, as a check on heat treatment given. Occasionally other metals. (*a*) Yes.
4. Nickel and chrome-nickel ordnance steels.

5. Carbon, nickel, nickel-chrome, chrome-molybdenum, chrome-vanadium steels. Duralumin, manganese-bronze. Cast aluminum alloys of copper, manganese and copper-silicon. (*a*) Yes.
6. Steel only. Others have been tried but readings are too low to be accurate so that large samples must be used and results have not been satisfactory. We are regularly testing micarta in the impact machine using 1-in. square pieces with notch ⅛ in. deep.
   (*a*) The brittle or soft non-ferrous metals tried so far have required a larger sample than standard to give high enough readings.
7. Iron, steel, cast iron, monel, compositions of all kinds. (*a*) Yes.
8. Steel and bronze. (*a*) Yes.
9. Alloy steels and a few aluminum alloys. (*a*) Yes.
10. Steel, aluminum and bronze. (*a*) Yes.
11. Steel.
12. Carbon and alloy steels of all varieties.
13. Steel.
14. Alloy steels.
15. Steel. Have never investigated any non-ferrous metals.
16. Magnesium alloys, aluminum alloys, cast iron. (*a*) Yes.
17. Ferrous and non-ferrous metals of any description. (*a*) Yes.
18. Heat-treated carbon and alloy steels.
19. Steel (notched), cast-iron and malleable-iron unnotched cylinders 1 in. in diameter, 8 or 12-in. span. Both for class demonstration purposes. (*a*) Have not tested non-ferrous metals.
20. Monel metal.
21. Tool and alloy steels. (*a*) No experience with non-ferrous metals.
22. Steel. (*a*) Do not test non-ferrous metals.
23. Steel. (*a*) Yes.

10. *Have you any views as to the relation of impact tests made on ferrous and non-ferrous metals and metallic and non-metallic materials?*

1. Will express no opinion at present.
2. (No comments.)
3. No.
4. No.
5. The values on most light alloys which we have tested are so small as to give very little indication of variation in properties.
6. We look favorably on a small machine for brittle and weak materials.
7. Not enough data are available to draw conclusions.
8. No.
9. (No comments.)
10. No.
11. No data.
12. No.
13. (No comments.)
14. (No comments.)
15. (No comments.)
16. We are of the opinion that on one and the same machine with the same type of specimen and notch, a single-blow impact toughness value indicates a definite condition irrespective of composition of material.
17. No.

18. (No comments.)
19. (No comments.)
20. (No comments.)
21. No experience.
22. (No comments.)
23. The values obtained are not always in accord with the other properties of the material. Each class should be considered separately, especially in comparing metallic and non-metallic materials.

11. *In what particular line do you consider impact tests to be of the most use, and do you think that the test is susceptible of standardization for particular rather than general application?*

1. Impact tests are particularly valuable where it is desired to obtain degrees of toughness by heat-treating process. It would seem that under conditions imposed by our present knowledge of impact, standardization would be more suitable for particular rather than general application.
2. (No comments.)
3. Checking heat treatment given alloy and carbon steels. It can and should be standardized as in this use it offers possibilities as a valuable acceptance test for purchasing.
4. As a substitute for transverse tests, to disclose impairment of ductility by non-metallic enclosures, woody structures, etc. As a means for scientific investigation. Standardization is considered undesirable at this time.
5. We use impact tests mostly to determine causes of failure.
6. In the study of materials that are subject to shock under serious conditions.
7. We feel that the Charpy test results do show many important qualities and that this test together with the results of a static test can be standardized for any particular steel for any particular purpose.
8. To study effect of heat treatment on alloy steels.
9. Should be standardized for particular application to highly stressed parts where heat treatment must be of very best.
10. Automotive use.
11. Yes.
12. It might be standardized for particular applications but would be difficult.
13. (No comments.)
14. (No comments.)
15. Steel to be subjected to various impacts. Susceptible to standardization for general application.
16. It is difficult to state in what particular line impact tests would be of the most value. We have used this test very extensively and to good advantage in both research and control work in the automotive field. In fact this impact test has practically supplanted chemical analysis as a means of production control in our plant. The above indicates that this test can be standardized for a particular purpose.
17. Our experience is not sufficiently extensive to warrant a definite answer to a question so general in character.
18. Relation of impact to service must be established first; hence general application impracticable. Impact tests applicable to particular cases, not to general ones.

19. In determining effects of heat and mechanical treatments on toughness of metals.
20. (No comments.)
21. Impact tests have been of great value to us in determining the behavior of steel parts under suddenly applied loads. Due to many variables difficult to control we doubt that the test is at present susceptible of standardization for general application.
22. To reveal the brittleness of steel, which is not revealed by the tension test nor by the Brinell hardness test.
23. In the investigation of new materials and new or special treatments. I believe a test such as the Izod could be standardized, using various sizes of machine to cover nearly all materials.

12. *Are you in favor of the American Society for Testing Materials attempting the standardization of impact testing at this time?*

(a) Should a single machine be standardized? If so, what machine?

(b) If more than one machine, should the same specimen be used for all machines?

(c) Suggest what you consider to be the desirable form of specimen for all types of machine or for any one type.

1. No. Complete standardization at the present time would retard a vast amount of experimental work.
   (*a*) No. (*b*) No. (*c*) Can give no suggestions at present.
2. (No comments.)
3. Yes. There is no American standard now either in machined or notched specimen and results reported are very confusing.
   (*a*) Charpy, or preferably a better one after investigation of proposed designs.
   (*b*) For different types of tests specimen dimensions cannot be similar. The shape, type and finish of notch should be same in all, and the depth regulated to give comparable results on different machines.
   (*c*) The square specimen with 45-deg. included angle, V notch with bottom curved with radius of 0.01 in. A sharp V cannot be secured constantly. Drilled notches are extremely difficult to make to standard specification in heat-treated steels.
4. No. (*a*) No.
5. Yes. (*a*) I do not think we should confine ourselves to a single machine. I believe both the Izod and Charpy should be standardized.
   (*b*) It would be very convenient to have the same specimen applicable to all machines.
   (*c*) I would suggest the Charpy Impact specimen attached hereto.[1] There seems to be no serious objection, however, to a round specimen.
6. Yes. (*a*) Do not believe any single machine could be made to cover the range.
   (*b*) Can see no objection to using the same specimen for all machines. At present it seems that relative size of test piece should be standardized.
   (*c*) We like the square cantilever type specimen with V notch very well.

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[1] See Fig. 1 (*b*).

7. The attempt should be made. A start should have been made long before this.
    - (*a*) A single machine if possible. What one is for the committee to determine.
    - (*b*) We believe that a machine should be standardized that will take a specimen that can be easily machined and the type of specimen should be so modified as to allow for this very necessary quantity. The machine should be as simple and as cheap as possible.
    - (*c*) We believe that some kind of notched specimen should be used. Just what kind is of less importance than that everybody should use the same specimen and that any shop can fabricate them cheaply.
8. Yes. (*a*) Yes. The machine most used abroad; I do not know which one.
    - (*b*) I do not know.
    - (*c*) Either square or round; the latter is standardized.
9. Yes. (*a*) Yes; either Olsen or Izod.
10. (*c*) ½-in. round with notch 0.05 in. deep.
11. Yes. (*a*) May require both cantilever and alternating impact.
    - (*b*) Alternating impact would require different specimens.
12. Do not think it is practicable at present.
    - (*a*) Yes; a machine testing the specimen as a beam.
    - (*c*) A square specimen with rounded notch. A round specimen would save much time and labor, but I do not find the results so reliable.
13. No.
14. No. (*c*) Round specimen, single blow.
15. Yes. (*a*) Yes. (*c*) Rectangular specimen with V notch.
16. We are heartily in sympathy with any attempt of the A.S.T.M. to standardize impact tests.
    - (*a*) A single standardized machine is preferable provided it is universal enough to cover the entire range of toughness with a fair degree of sensitivity and be equipped for both tension and transverse impact tests. Proper sensitiveness for the entire range might be obtained by using different hammers or by loading up a given hammer to a given weight. We do not know what success the Charpy machine has met in this respect, but do know that this principle has proven very satisfactory in the Eden-Foster Impact Fatigue Machine.
    - (*c*) We have had no experience with types of specimens other than that described herein.
17. Yes, if experience indicates desirability of standardization.
    - (*a*) Yes, if there is one "best" machine.
    - (*b*) If experience warrants.
    - (*c*) Our experience not sufficiently extensive to warrant a decision.
18. In favor of determining what machines should be considered for recommended practice first.
    - (*a*) In favor of one machine if decision can be reached.
    - (*b*) Desirable, but doubt feasibility.
19. Yes.
    - (*a*) No.
    - (*b*) Yes.
20. (No comments.)
21. No.
22. Yes. (*a*) Yes, Charpy. (*c*) Charpy-Mesnager test specimens.
23. Yes. (*a*) Izod. (*b*) No. (*c*) For the Izod machine, we suggest the figure attached hereto.[1]

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[1] See Fig. 2 (*c*).

REVIEW OF THE WORK ON IMPACT TESTING DONE BY THE BRITISH ENGINEERING STANDARDS ASSOCIATION.

By T. D. Lynch.[1]

In 1921, Committee E-1 appointed a special committee consisting of Messrs. W. H. Bassett, A. N. Johnson, Richard Moldenke and the writer, as chairman, with instructions to review a considerable amount of data that had been received from the British Engineering Standards Association in regard to impact testing of metals. The committee presented its report to Committee E-1 in June, 1921, and the present paper is an abstract of that report.[2]

The British Engineering Standards Association is composed of representatives of the Association of Civil Engineers, Mechanical Engineers, Electrical Engineers, Naval Architects, and the Iron and Steel Institute. It was founded in 1901 and incorporated in 1918.

The details of the work accomplished by the members of the several divisions of the Association are given in C. L. reports, many of which have been reviewed; and the following comments are made on those reports that were most representative of this work.

C. L. 3058.—Dr. Stanton shows that resilience varies with size of test piece for all notched bar impact values, but this difference is lowest for fragile materials and greatest for ductile materials.

C. L. 3157.—Dr. Stanton describes three kinds of notch tests:—(1) The Charpy notch; (2) The sharp "V" notch 2 mm. deep; (3) The rounded "V" notch 2 mm. deep. He shows much greater uniformity in No. 3, the rounded "V" notch.

C. L. 3500.—National Physical Laboratory gave record of tests on "V" notches, sharp and with $\frac{1}{6}$ mm., $\frac{1}{2}$ mm., and $\frac{2}{3}$ mm. radii, showing that increase of radius increased the energy absorbed.

C. L. 3606.—Dr. Stanton shows that the deep rounded "V" notch is preferable to the short "V" notch.

C. L. 3732.—Charpy advocates deep notches cut to drilled holes.

C. L. 3757.—The Steel Research Committee suggested the "V" notch on account of difficulty of drilling the hole for Charpy test.

C. L. 3886.—National Physical Laboratory suggests the 45 degree "V" notch 2 mm. deep and recommends that these tests be made to determine the relation of $\frac{1}{4}$ mm. radius to $\frac{2}{3}$ mm. radius.

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[1] Engineer of Material Tests, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

[2] The complete report of this special committee, including illustrations of standard test specimens and other details, is on file in Committee E-1 on Methods of Testing and is available for inspection of any members who may be interested.—Ed.

C. L. 4226.—National Physical Laboratory gave opinion that mechanical difficulties of preparing test pieces having deep notches like Charpy is so great as to preclude their general use. They recommend deep rounded "V" notch and test piece for alloy steel to be 10 by 10 by 40 mm. span with ¼ mm. radius.

C. L. 4370.—National Physical Laboratory mentions Captain Philpot's report showing that ⅔ mm. radius in a shallow notched specimen would not discriminate between correctly and incorrectly heat-treated steel, but would so indicate with 5 mm. deep notch having ⅔ mm. radius.

C. L. 4408.—Sir Robert Hadfield states that the Fremont (falling tup) and Guillery (rotary flywheel) machines give impact velocity of 8.85 meters per second.

C. L. 4833.—Hadfield states that since the object of shock testing is to detect variations of resistance between rapidly and slowly applied stresses, the velocity of impact should be considered and advocates the determination of a curve to show the reduced resistance to shock as velocity increases and also states that the velocity should be great enough to determine brittleness in all specimens.

C. L. 5269.—Hadfield and Main give comparative tests on Izod and Fremont machines, each with its own type of specimen, showing greater difference between tough and brittle steel on the Fremont machine.

C. L. 7691.—Cornu-Thenard states that the velocity effect on notch tests has importance only on very low carbon steels.

C. L. 8173.—Hadfield states that speed effect is important only on mild steels.

The British Engineering Standards Association published their Report No. 131 under date of August, 1920, giving their conclusions of the work done up to that time. This report states that:

> "In view of the large use of notched bar tests, and the diversity in the dimensions of the test pieces at present used, it has been considered desirable that the test should be standardized, and this report gives the standard dimensions of the test pieces and the form of notch recommended, as well as a number of other particulars."

It was decided by this Association that the test piece should be fractured by a single blow of a falling tup, a pendulum, or a revolving flywheel; that the work expended in fracture should be measured by the difference of the striking energy before and after impact; that in pendulum machines the pendulum should be supported on knife edges or ball bearings; that the centers of gravity of the pendulum and test piece and the point of impact should be in the middle plane of oscillation of the pendulum; that the center of percussion of the pendulum should be at or slightly above the point of impact; that the results, in some materials, depend on the striking velocity which should not in any case be less than 3 meters per second; that the weight of the anvil block and its foundation should be at least 40 times the weight of the tup or pendulum; and that the results obtained from impact machines, using their respective notched bar test specimens, do not appear to be materially different provided the machines are properly constructed, calibrated, and used, and the striking velocity not substantially different.

Striking Energy and Velocity.—The striking energy and velocity of six types of impact testing machines in quite common use are given in the following table:

TYPE OF MACHINE.	STRIKING ENERGY, KGM.	STRIKING ENERGY, FT-LB.	STRIKING VELOCITY, M. PER SEC.	STRIKING VELOCITY, FT. PER SEC.
Charpy, pendulum	30	217	5.3	17.39
Izod, pendulum	16.6	120	3.5	11.48
Fremont, falling tup	20	144.7	8.85	27.37
Fremont, falling tup	60	434	8.85	27.37
Amsler, pendulum	30	217	4.95	16.57
Guillery, rotary flywheel	60	434	8.85	27.37

Form of Notch.—Various forms of notch have been adopted by different engineers, and the work required to fracture is different according to the type of notch used. After much investigation it was decided that the standard notch should be a "V" notch of 45-deg. angle with a radius at the bottom of the notch of 0.25 mm.[1]

Size of Test Piece.—Test pieces of 15 by 15 by 80 mm. and 30 by 30 by 160 mm. have been used by various engineers. Considering the cases in which the notched bar test is most likely to be useful, and the difficulty of obtaining test pieces of so large a size, it has been decided that a smaller test piece is more practical.

A trustworthy relation between the work of fracture in test pieces of different sizes has not been found, but there is evidence that it is probably different in different materials.

For the present it is recommended that the results of tests should be expressed in kilogrammeters, and that only results on test pieces of identical dimensions should be compared.

Units Employed.—It was also recommended that all dimensions should be expressed in metric units; the dimensions of the test piece in millimeters, the striking velocity in meters per second, and the work of fracture in kilogrammeters.

Number of Tests.—At least three tests should be made and the average result taken.

RECOMMENDATIONS CONTAINED IN REPORTS.

The British Standard Notched Bar Test Piece shall be 10 by 10 mm. in cross-section.

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[1] See Fig. 2 (*b*), p. 88.—ED.

Where this size of test piece cannot be obtained from the material, subsidiary standard test pieces having cross-sections of 10 by 5 mm. and 5 by 5 mm., respectively, shall be employed.

The standard notch recommended for the 10 by 10-mm. specimen is the V notch, 2 mm. deep, included angle 45 deg.. with radius at bottom of notch equal to 0.25 mm. For the subsidiary test pieces mentioned above, a notch 1.5 mm. in depth is recommended, the other dimensions being the same.

Recommendations are also made for the angles and radii of the supports and strikers for the beam-type and cantilever-type specimens.

Adaptation of the 30 kgm. Charpy testing machine for testing the subsidiary standard 10 by 5-mm. and 5 by 5-mm. beam type test pieces was recommended.

It was recommended that new grips should be made for the Izod testing machine in order to adapt the machine for testing the subsidiary standard 10 by 5-mm. and 5 by 5-mm. test pieces. These grips should be 11 mm. higher and the grip behind the specimen should be 5 mm. thicker than the grips supplied with the machine for testing the 10 by 10-mm. specimens. The new grips should be hardened to give a Brinell hardness of not less than 440.

Mr. T. E. Stanton and R. G. C. Batson, in a paper before the Institution of Civil Engineers, November 30, 1920, brought out the importance of similar section of impact test specimens where the results are to be compared. As an example, they show that for specimens geometrically similar to the British standard test piece, of two materials "A" and "B", when the specimens are 10 by 10 mm., "A" is 230 per cent better than "B", and when the specimens are 63 by 63 mm., "A" is only 50 per cent better than "B". In view of this, they state that the British Engineering Standards Association have decided that only results on test pieces of identical dimensions should be compared.

In view of the foregoing reports and recommendations of the British Engineering Standards Association, it is evident that there is a real need for a standardization of the main features of impact testing by the American Society for Testing Materials, including size of test specimen; type of test specimen, whether beam or cantilever; depth of notch, whether "V" or straight slot; rounding of bottom of notch; striking speed; striking energy; whether or not the test is accomplished in one stroke or many strokes in one or more directions; and whether or not the same test specimen and stroke will be suitable for different materials.

MEASUREMENT OF PRESSURES CAUSED BY IMPACT.

By C. E. Margerum.[1]

That some have gained the impression that the strength of materials may be measured in foot-pounds is a not unnatural result of the publication of numerous articles on the subject of impact testing in which the results are expressed in terms of energy. The ease with which the energy of a moving body, especially a pendular body, may be measured, as opposed to the difficulties attending the determination of the pressures caused by impact, has led to the introduction of tests in which the energy required to break test pieces by impact is determined. In the absence of facilities for satisfying the desire for information as to the strength and ductility, separately, under impact loading, this type of test has been adopted widely in the belief that information as to the properties of material subject to shock is to be deduced from comparison of the amounts of energy required to break test bars of various materials under precisely defined, and therefore comparable, conditions.

It was perhaps inevitable that with the spread of the use of this test to men concerned primarily with the properties of materials, rather than with physics, the inapplicability of units of energy to the measurement of pressures has not always been kept in mind. Articles appear with increasing frequency in the technical press in which the arguments are based on the statement or assumption that the impact value in units of work is a measure of the ability of the material tested to withstand impact stresses in practice. Without any desire to deprecate the value of current impact tests, it may be stated that it must be a very exceptional case in which good design calls for such use of material that this assumption is even approximately true. On the contrary, impacts are commonly taken on springs, and the springs are hardened, an operation which greatly reduces the work value of the material in the impact test. In general, parts subject to repeated direct impacts from rigid objects at any but very low velocities are usually hardened, sometimes hardened and drawn partially, but seldom used in the condition in which the material will give the highest impact test.

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[1] Metallurgist, U. S. Naval Ordnance Plant, South Charleston, W. Va.

That the properties required of parts subject to severe impact stresses are such as to call for the use of material in a more or less hard state rather than in the condition in which it will consume a larger number of work units in an impact test, is not a contradiction of the value of the impact tests, but only of an erroneous application of the results in the assumption that the number of foot-pounds consumed is a direct index of the ability of the material to withstand impact service.

It is not the province of this paper to discuss wherein the usefulness of Charpy and other impact tests does lie, but it would be of little use to go into the subject of measurement of the pressures caused by impact if a determination of energy units would serve the purpose. Measurement of pressures produced by impacts is of interest in determining the stresses to which a structure or a part is to be subjected, as well as in determining the capacity of the material to withstand such stresses. Both uses will be considered in this paper.

A number of methods for making the determinations of these pressures have been devised. They may be classified according to the principles on which they operate as time-space, deflection, and deformation methods, each of which has its advantages and its limitations. It is greatly to be regretted that the disadvantages and limitations are so pronounced.

TIME-SPACE METHOD.

The time-space method utilizes the principle that the pressure exerted on or by a freely moving body may be calculated from the change of velocity which this pressure produces in a given time interval. It requires an accurate record of the center of percussion of the moving body with respect to time, which is usually obtained by employing a device for tracing a curve on a revolving drum. Apparatus for determining impact pressures by this method is described in another paper[1] at this meeting, so discussion here will be confined to advantages and limitations of the method.

From a theoretical standpoint the time-space method is very inviting, as it does not modify the effect of the impact by interposing any cushioning effect, it does not depend on knowledge of the elasticity or deformability of materials under loads of brief duration as the two other methods do, and it would allow a determination of the value of the pressure in each of the various stages of the impact. If this last advantage could be realized it would be of very great value, as it would permit the drawing of stress-strain diagrams for specimens tested by impact.

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[1] See p. 117.—ED.

For as close an approximation of such diagrams as are available, we present in Fig. 1 two pressure-deformation curves of 10 by 10 by 53.3-mm. Charpy type notched bars tested by M. Andre Cornu-Thenard as beams after the manner of the Charpy test, except that the load was applied slowly instead of by impact so that the deformation could be followed.[1] The properties of the steels are given below:

	Elastic Limit, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation, per cent.	Contraction, per cent.	Work Value. Notched 10 by 10 by 53.3-mm. Bar.	
					Slow Action, ft-lb.	Impact, ft-lb.
Steel *b*......	47 000	64 000	39.0	70.3	124.7	152.5
Steel *e*......	134 000	144 500	21.2	53.3	50.0	76.8

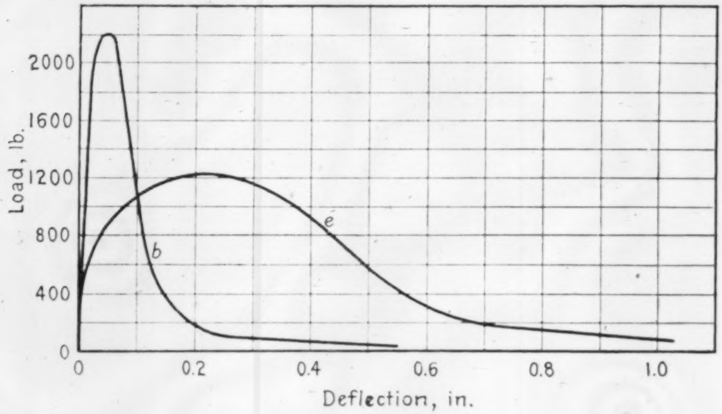

FIG. 1.—Load Deflection Diagram Obtained from Impact Tests of Charpy Notched Bars 10 by 10 by 53.3-mm. (Notch 1.3 mm. in diameter, 5 mm. deep.) Load Applied Slowly Instead of by Impact. Diagram Replotted to English Units from Determinations made by Andre Cornu-Thenard.

The steels are normal in having materially greater work-values when the bars are broken by impact than when the pressure is applied gradually.

If a test is to be of service as a direct indication of the performance of the material under impact in service it is of major importance to know whether the properties of the material are as represented by curve *b* or by curve *e*, and whether the excess (or deficiency) of work units by impact over the result of slow action results from a change in the elastic limit, in tensile strength, or by a prolongation of the

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[1] M. Andre Cornu-Thenard, *Revue de Metallurgie*, 1920, p. 550.

TABLE I.—TIME-SPACE STUDY OF CHARPY IMPACT TESTING MACHINE.

Weight of pendulum, 50 lb. Velocity at point of impact, 207.53 in. per second.

	Distance past point of impact or deflection of the bar, in.										
	0.01	0.02	0.05	0.08	0.10	0.20	0.30	0.40	0.50	0.60	1.00
TIME OF TRAVEL OF KNIFE EDGE THROUGH DESIGNATED DISTANCES FROM STRIKING POINT, IN UNITS OF $\frac{1}{100\,000\,000}$ SECOND.											
Pendulum swinging free	4 819	9 637	24 093	38 549	48 186	96 372	144 558	152 744	240 930	289 116	481 860
Pendulum breaking bar "*b*" of Fig. 1	4 820	9 642	24 152	38 727	48 487	97 900	148 520	200 370	253 250	306 750	523 830
Pendulum breaking bar "*e*" of Fig. 1	4 820	9 648	24 236	39 000	48 930	99 190	149 410	199 670	249 950	300 250	501 450
DISTANCE BETWEEN POSITION OF PENDULUM AND POINT WHERE IT WOULD HAVE BEEN HAD IT NOT ENCOUNTERED THE NOTCHED BAR.											
Pendulum breaking bar "*b*" of Fig. 1		0.00001	0.00012	0.00037	0.00062	0.00315	0.0082	0.0158	0.0256	0.0366	0.0869
Pendulum breaking bar "*e*" of Fig. 1		0.00002	0.00029	0.00093	0.00154	0.00538	0.0101	0.0144	0.0187	0.0230	0.0406

Limit of elasticity, Steel "*b*"... 550 lb. at 0.0058 in. deflection.
Limit of elasticity, Steel "*e*"... 1 900 lb. at 0.0200 in. deflection.
Maximum load, Steel "*b*"..... 1 210 lb. at 0.2200 in. deflection.
Maximum load, Steel "*e*"...... 2 200 lb. at 0.0500 in. deflection.

horizontal portion of the curve, as it is evident from the fragments that the ultimate distortion of the test piece is the same for both methods of loading.

To test the competence of the time-space method to determine the limits of elasticity and maximum load in impact tests, calculations were made of the time-space curves which would result if accurate tracings were obtained from Charpy tests of samples having the characteristics under impact that are represented by curves *b* and *e* of Fig. 1. The curvature of the time-space diagram is so slight that it is useless to show it. The numerical results presented in Table I show the futility of attempting to measure impact pressures of this kind by the time-space method. Conditions could be improved by lightening the ram, but this changes the characteristics of the test; and if the weight is made so small that it will just break the bar the curve still does not give a measurable difference between curves *b* and *e* in the first 0.02 in. of deflection, which includes the limits of elasticity.

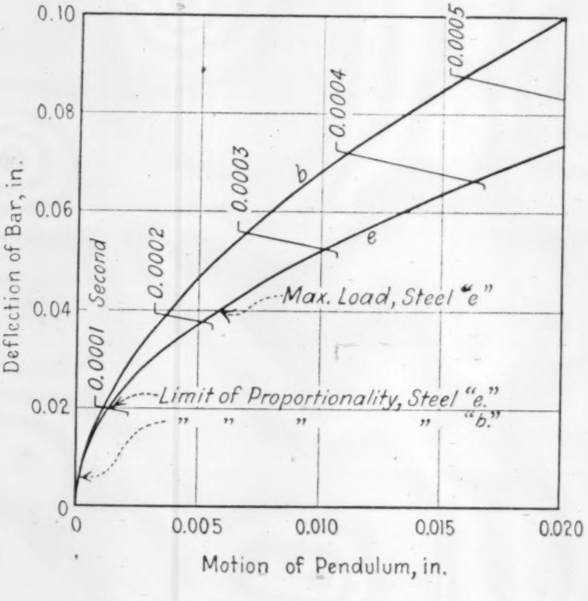

FIG. 2.—Portion of Curve for Charpy Bars Broken Against a Stationary 20-lb. Pendulum. Ram Weighing 200 lb. Moving 17.3 ft. per second.

The most easily read time-space curve of the breaking of a notched bar under conditions equivalent to the Charpy test would be produced by means of a modification of the arrangement of the apparatus by which the bar and its supports would move at the required velocity, and the bar be broken against an initially stationary pendulum. Fig. 2 gives the curve for the movement of a 20-lb. pendulum accelerated by breaking bars *b* and *e* against it by the action of a 200-lb. ram traveling at the same speed as the Charpy pendulum at the point of impact. It will be noted that though the difference between curves for *b* and *e* appears shortly after the limit of elasticity of steel *b* is passed, the distances to be measured are still well outside our capacity for recording and measurement on a curve.

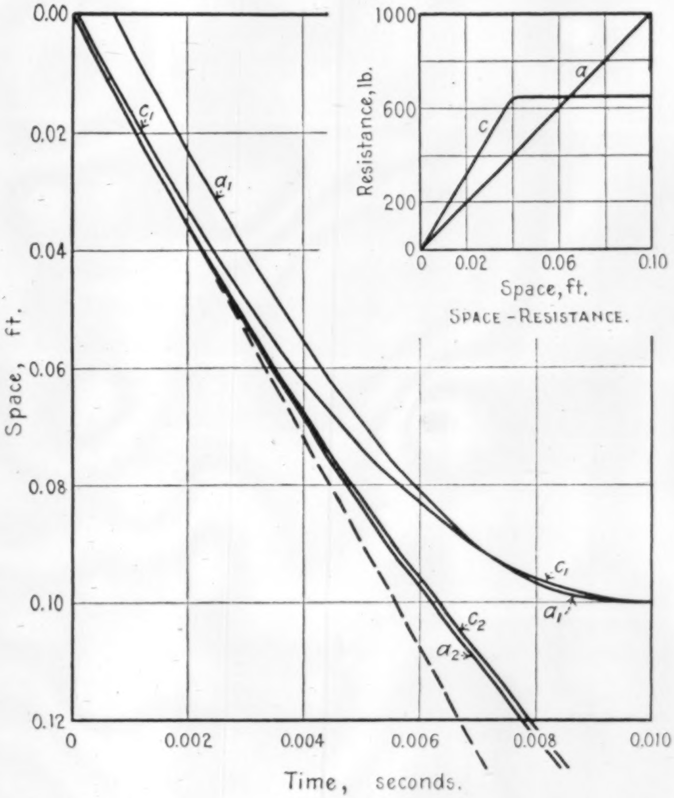

FIG. 3.—Time-Space Curves Representing the Motion of Weights for Falling 5 ft. and Meeting the Resistance Shown in the Space-Resistance Diagram in the Upper Right Corner.

Measurement of Cushioned Impacts by the Time-Space Method.—Though we cannot follow the pressures in the Charpy and similar tests by the time-space method, there still remains the possibility that the method may be useful in determining the pressures that finished structures bear in practice. Time-space curves in Fig. 3 represent the motion of weights after falling 5 ft. and meeting the resistances shown by curves *a* and *c* respectively in the diagram in the upper right corner of the figure. Curve *a*, representing uniformly increasing resistance, is typical of that offered by elastic materials of which the limit of proportionality is not reached, and curve *c* of resistance in which deformation occurs. The total energy in both cases is the same but the maximum pressure is 1000 lb. in curve *a* and only 650 lb. in curve *c*.

In the case of curves a_1 and c_1, which are for weights of 10 lb. each which are completely arrested, there is an appreciable and measurable difference between the two curves at the point of principal interest, that is at their peaks, but the difference is so slight compared to the difference in pressures that determinations even from perfect curves would have only a moderate degree of accuracy.

Curves a_2 and c_2 of the same figure represent the motion of weights of 20 lb. each instead of 10 lb. as in curves a_1 and c_1, thus having an excess of 100 per cent over the amount of energy necessary to overcome the resistance. It will be seen that neither the moment of impact nor the moment the resistance ends can be found from these curves. As an illustration of the effect of this circumstance on the accuracy of a determination, let us consider the effect of a variation from curve *a* (Fig. 3) by which the increase of resistance stops at 900 lb., but continues at 900 lb. for 0.00055 ft. farther than in curve *a*, to keep the total energy of resistance the same as before. The maximum pressure will be 10 per cent less than of curve *a*, but the difference between the curve for this case and curve a_2 is that between 0.09 in. and 0.10 in. from the point of impact the curve is gradually shifted over to the left a distance equal to 0.00003 second.

Formidable obstacles to the use of the time-space method in addition to, and intensified by, the minuteness of the distances and time intervals to be measured, lie in the great difficulties in obtaining true curves and magnifying them to sufficient size. Some of the requirements are:

1. A fixed datum point, or one having a known and resolvable motion, must be provided; and this must be free from vibrations or tremors of a magnitude that would affect the results. In the presence of heavy impacts this condition is difficult to meet.

2. The tracing mechanism must not be deflected by the stresses incident to their functioning. This precludes the use of multiplying devices to trace the curve on an enlarged scale.

3. The time must be recorded accurately, with minute subdivisions.

4. The tracing point must record the motion of the center of percussion of the acting mass. This is possible only for substantially rigid bodies as the center of percussion of a non-rigid body is not a fixed point. The blow must strike squarely so that the motion is all in a straight line, as even a slight deflection out of line will vitiate the results. For instance, if the point of attachment of the tracing point in the case of the curves of Fig. 3 is assumed to be 2 in. to the side of the center of percussion and 2 in. above the point of impact, then if the axis of the striking body is deflected 1 deg. from its original direction the error will be 0.003 ft. up or down on the curve if the deflection is toward or away from the card, which is more than the difference between curves a_2 and c_2.

The difficulties and disabilities of the time-space method have been dwelt on at length because the theoretical advantages of the method make it very inviting, and a great deal of time and money have been spent by various investigators on attempts to utilize this principle. It is suggested to any one who is inclined to build apparatus for this method, or to accept results obtained by it, that he first calculate curves which would be obtained for the particular case involved, and consider these in connection with the facilities available for recording and measuring the curves, and the liability of errors in making the record.

DEFLECTION METHOD.

The pressure caused by impact is measured by the amount of deflection of an elastic body in the deflection method of determining these pressures. The obstacles to the measurement of impact pressures by the deflection of springs has limited the application of this method in practice to cushioned impacts at low velocities.

A movement of the spring indicates the pressure, but to cause this movement in the brief time interval of an impact of a rigid body, suddenly arrested, involves the production of heavy local pressures due to the inertia of the parts of the spring and any attachments thereto which move as the spring is deflected. It is only after the parts in contact with the moving body have attained its velocity and are moving with it, that the spring measures the pressure. A greater pressure at the point of impact may have occurred before this condition is reached. To secure true results the materials at the point of impact should be of a yielding nature, the weight of the parts which receive the blow and move with the moving body during its deceleration should be comparatively slight and their motion limited, and the period of oscillation of the weighing system should be less than the time interval in which the motion is arrested.

Where the deflection method is applicable it probably is the best method of all, though its general use is confined to conditions which hardly correspond to the general conception of impact. The manograph[1] measures pressures at rates of variation of the order of those caused by impacts, and it is to be hoped that apparatus will be devised for recording the pressures in impact testing by a deflection method.

Both the time-space curve and the deflection of springs have been used in vertical drop types of impact testing machines to determine the amount of energy remaining in the ram after breaking the bar. For this use neither is open to any of the criticisms which have been made of their employment to measure impact pressures. The deformation principle was used in the earliest machines for determining the work of rupture to record the residual energy of the ram, but while it accomplished its purpose it was abandoned in favor of methods of equal accuracy which do not involve the considerable amount of labor which the use of the deformation method entails.

THE DEFORMATION METHOD.

The one method of measuring momentary pressures that has attained the state of established successful use is that in which the pressure is caused to record itself by deforming a piece of metal of which the amount of deformation for given static loads is known.

Ordnance calculations for two generations at least have been based on determinations of explosion pressures made in this way, and the method is in every day use in every country in which modern artillery is made. The apparatus used is shown in Fig. 4 which is self-explanatory. The copper cylinders are made in large lots with care to secure uniformity. Several from each hundred are subjected to test pressures under an ordinary tension testing machine and the amount of upsetting measured. The results having been found to be consistent, the remainder of the lot is issued for use. The type of gage shown in the figure is laid loose at the rear of the powder in a gun; other types differ by having external threads provided for securing the gage in place where this is necessary. The grease seals the carefully lapped joints against any leakage of powder gases during the brief interval of explosion pressure, and the gas pressure acting on the exposed end of the plunger shortens the copper cylinder the amount that its companion pieces were upset by the same number of pounds under the testing machine. Comparisons of momentary pressures of explosions with those applied by the testing machine are made directly without any coefficients or corrections for any hypothetical difference between effects of momentary and longer sustained loads, as conclusive investigations have shown this to be the proper course.

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[1] A steam-engine indicator for very high speed engines; the motion of a diaphragm is magnified by means of a beam of light. *Power*, June, 1907.

Application of the deformation method to the measurement of impact pressures is not limited, like the methods previously discussed, to low velocities and cushioned blows; its one limitation is that it records the maximum pressure only. Its merits within this limitation deserve wider recognition than is accorded it at the present time.

Though the use of the deformation method has been long established in a branch of industry which is probably more thoroughly developed along scientific and mathematical lines than any of the more common arts, and notwithstanding it has been the subject of exhaustive investigations conducted by men of the highest standing, such as Messrs. Sarrau and Vielle, and M. Georges Charpy, who have pronounced it free from appreciable error,[1] there is a tendency among the majority who may not be familiar with these circumstances to urge speculative objections as to the validity of the results. These objections in general are based more or less subconsciously on the idea that deformation of metals is of the same nature as the flow of viscous liquids, and consequently that the amount of deformation is a function of time and pressure.

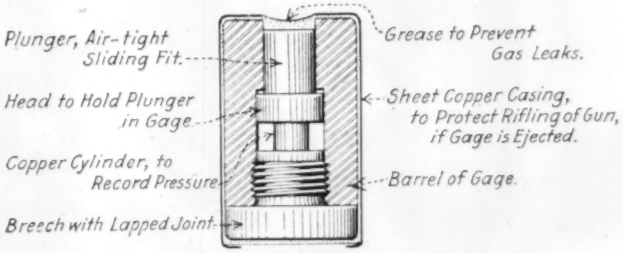
Plunger, Air-tight Sliding Fit.
Head to Hold Plunger in Gage.
Copper Cylinder, to Record Pressure
Breech with Lapped Joint
Grease to Prevent Gas Leaks.
Sheet Copper Casing, to Protect Rifling of Gun, if Gage is Ejected.
Barrel of Gage.

FIG. 4.—Crusher Gage.

While the matter is wholly theoretical and academic in that we are dealing with a difference between deformations caused by prolongation of the period of loading for various though brief periods of time, when the total increase of deformation for the whole period which includes the intervals in question is not great enough to be detected, still it may be of interest to give the subject of the flow or creep of metals under load some slight attention. It is a matter of common knowledge that, in making Brinell hardness tests, maintaining the pressure on the ball for thirty seconds will often give a perceptibly larger impression than will be made in four or five seconds; hence the requirement of a definite period of loading in the Brinell test. Now the upsetting of the cylinders of the crusher gage is similar to the indenting of material by the Brinell ball (in fact the writer prefers to record impact pressures by indentation by a ball rather than by upsetting of cylinders), and as steel creeps noticeably under the Brinell ball from the fourth or fifth second after the application of the load to the thirtieth second, and less from the thirtieth to the sixtieth than from the fifth to the thirtieth, there is reason for conjecture as to whether this creep is not occurring at a rate many times greater during the first small fraction of a second than in the first period in which it can be easily observed.

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[1] *Journal*, Iron and Steel Institute, Vol. XCVI, No. 11 (1917).

Experiments were made in which the period of loading was varied from small but unmeasured fractions of a second to two seconds. The period of loading within these limits had no appreciable effect on the amount of deformation produced, though a difference of not over two per cent might have escaped detection.

To carry the experiments to the other extreme, a piece of the steel used in recording impact pressures was indented by a 10-mm. steel ball under a tension testing machine. The pressure was run up as rapidly as possible to 10,000 lb., the motor disengaged, and the beam kept balanced by running the machine by hand as the ball gradually sank into the sample. The driving gear of the machine was turned one tooth at a time, and the penetration of the ball recorded in terms of the number of teeth which had to be advanced to keep the beam floating. As the results were somewhat irregular and not consistent even for repetitions on the same sample, only the general sense of the phenomena common to all samples will be given, except to state in passing that an increase of indentation equivalent to an increase of 3 per cent of load required about an hour. The rate of creep held nearly uniform from the third to the fifteenth or twentieth second after the first application of the load, then fell off gradually to a lower rate which was maintained for a long time; creeping was still in progress at the end of three hours.

A very interesting point is that action continues after the load is removed, so that if the pressure is relieved and replaced after several minutes, the ball sinks to about the same depth which it would have reached if the load had been maintained continuously, while if the load is removed and replaced within a few seconds no appreciable enlargement of the indentation results. If two or three days intervene between applications of the load a greater deformation is made than by continuous loading for three hours.

It would seem then that the creeping of steel under load is essentially different from the flow of viscous material, and may possibly be the result of a kind of self-tempering or rearrangement of the steel following the hardening by cold work due to the forcible deformation by the ball when the load is first applied. At any rate there is definite evidence that the creep attains no such high velocity in the earliest fraction of a second of the period of impact as it would have to have if it were to be a source of material error. Accuracy in calibrating the crusher may be slightly reduced, however, by prolonging the duration of the test load for more than a few seconds.

The advantages in using a ball to make the record of the pressure by indenting a calibrated piece, rather than using small cylinders, are (1) that the apparatus can be made simpler and lighter in many cases, with a reduction of friction and inertia errors, (2) the record pieces do not have to be machined to exact size (since the pressure need be only approximately normal to the record piece), (3) there is only one measurement to be made and the record may be checked at any time, (4) the test load can be applied to the same piece used in making the record instead of to a companion piece, (5) the calibration may be checked on the same piece after the determination if desired, and lastly, (6) the depth of penetration is proportional to the pressure, which makes calibration easy and simplifies calculations when it is desired to determine the amount of energy used in making the indentation.

MEASUREMENT OF PRESSURE IN IMPACT TESTS OF NOTCHED BARS.

At the last annual meeting the writer described an apparatus for determining the strength of small beams of hardened steel when broken by impact.[1] This apparatus, with slight modifications of the parts in contact with the specimen, is also used experimentally to determine the maximum load before rupture of notched bars of the type of bar *e*, Fig. 1. As it is desirable to be able to test more ductile bars than is practical with this device, and since it is preferable, both from the standpoint of economy and because of the discrepancy often found between bars taken from the same piece, to make the measurements of strength on the same bar that is used for the determination of work-value, the pressure-recording device may be incorporated to advantage in the machine which is used to determine the work of rupture. Fig. 5 shows the application to the Charpy machine. The whole apparatus for recording the pressure is placed in the knife-edge of the machine. The pressure is automatically recorded by the indentation of a cube of heat-treated steel. Each cube will answer for five tests and a test load. The small amount of energy expended in making the indentation must be deducted from the total energy consumption indicated by the machine to obtain the amount used in breaking the bar.

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[1] C. E. Margerum, "A Test for Shock Strength of Hardened Steel," *Proceedings*, Am. Soc. Test. Mats., Vol. 21, p. 876 (1921).

While this device will give only the maximum load, it records the load in a very simple and definite way, and if used in conjunction with an apparatus for drawing the stress-strain diagram of notched bars under gradual loading, nearly complete information as to the strength of the material under impact, the effect of the notching, and the effect of the impact may be obtained.

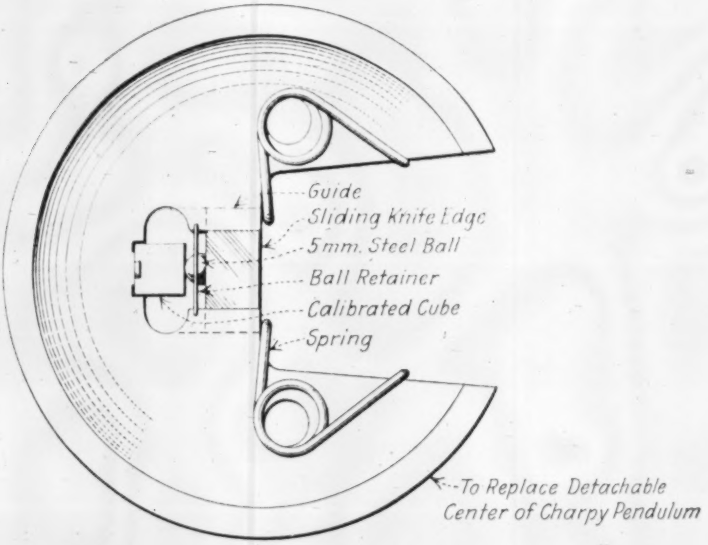

FIG. 5.—Apparatus for Recording Maximum Pressure in Charpy Impact Test.

The application of the deformation method to the measurement of impact pressures encountered in service by the use of one or more balls and calibrated pieces is quite simple, the principal precautions necessary being to bring all of the effect of the impact on to the measuring device, and to avoid excessive weight in the part which receives the blow and transmits the resulting pressure to the ball. This last precaution is taken to avoid error from inertia, but as the smallness of the travel of the ball minimizes the inertia effect this requirement presents difficulties only where the impact is between hard bodies at considerable velocities. In such impacts the deformation of the moving bodies themselves sometimes can be used to measure the pressure.

MEASURING FORCES IN IMPACT.

By Armin Elmendorf.[1]

In attempting to measure forces introduced by impact upon beams supported at the ends and struck at the center, two physical means suggest themselves. In one of these, suitable spring supports at the ends of the beam are compressed and autographic records of spring compression and beam deflection are obtained; and in the other the beam is supported rigidly at the ends and position-time curves of the falling hammer are obtained by means of a rotating drum. Several objections may be waged against the first method. It would be very difficult mechanically to devise a piece of apparatus that would record the data accurately and yet not possess inertia errors that would seriously vitiate the results; and it could also be maintained that a test of this kind is simply a rapid loading test and not truly an impact test if by impact a non-yielding resistance at some part of the member struck is implied. The second method is, therefore, probably the more feasible of the two.

Assuming that an impact test is to be made upon a beam rigidly held at the ends and struck at the center, the next question that arises before the method of measuring forces can be decided upon is whether the blow is to be of sufficient magnitude completely to rupture the beam or whether fracture is to be obtained by repeatedly increasing the blow until rupture takes place. The latter method of loading is discussed by Mr. T. R. C. Wilson in his paper on testing wood in impact. His paper forms a part of this Symposium.[2] By noting the height at which an impact hammer is dropped and repeatedly measuring the corresponding deflection introduced it is possible to obtain the stress at the elastic limit under impact, as well as the modulus of elasticity assuming a certain deflection distribution. No information about the force at rupture can be obtained in this way, however, unless loading all the way to rupture is elastic; nor can the destruction of the test specimen be studied other than by visual inspection of the fracture at the end of the test. The method pursued by the writer in studying forces under impact gives the maximum resistance exerted by the specimen and makes possible a study of the progressive breaking down of a test specimen after its maximum resistance has been exceeded. It depends essentially upon the possibility of obtaining a clear position-time or deflection-time curve for the center of the beam and mechanical means for operating upon such a curve to draw its first and second differential curves. To determine the feasibility of this procedure, tests were made by the author using the Hatt-Turner drop-testing machine at the Forest Products Laboratory, Madison, Wis. This machine is illustrated in Fig. 1.[1] Its construction is well known and it is only necessary to state here that a hammer weighing 50 lb. is allowed to drop upon the center of a beam rigidly supported at the ends on a heavy base. This hammer is provided with a brass pin or stylus, which draws a line on a sheet of metallized paper mounted on a drum that rotates rapidly about a vertical axis. The speed of the drum is recorded on the paper by means of a stylus fastened to the end of one prong of a tuning fork which is clamped to the frame of the machine. The tests were made upon 2 by 2-in. beams of yellow pine, spruce, and Douglas fir 44 and 50 in. long. Similar beams cut from the same boards were also tested in static bending for purpose of comparison. In each case the complete load-deflection curve was obtained. Six beams were tested in impact and five in static bending.

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[1] Consulting Engineer, Haskelite Manufacturing Corp., Chicago, Ill.

[2] See p. 55.—Ed.

The effective force at the center of the beam equivalent to a center load in static bending is given very closely by the equation[2]

$$F = W_t - \left(W_t + \frac{17}{35} W_b\right) \frac{1}{g} \frac{d^2s}{dt^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which W_t = weight of the hammer,
W_b = weight of the beam,
g = acceleration of gravity, and
$\frac{d^2s}{dt^2}$ = upward acceleration at any instant.

In order to obtain a graphical representation of the acceleration of the hammer at any instant the writer first devised the differentiating machine shown in Fig. 2(*a*). The deflection-time curves obtained from the impact tests were all operated upon by means of this machine. One of two other instruments for the same purpose subsequently designed is illustrated in the same figure.[3] The best results are

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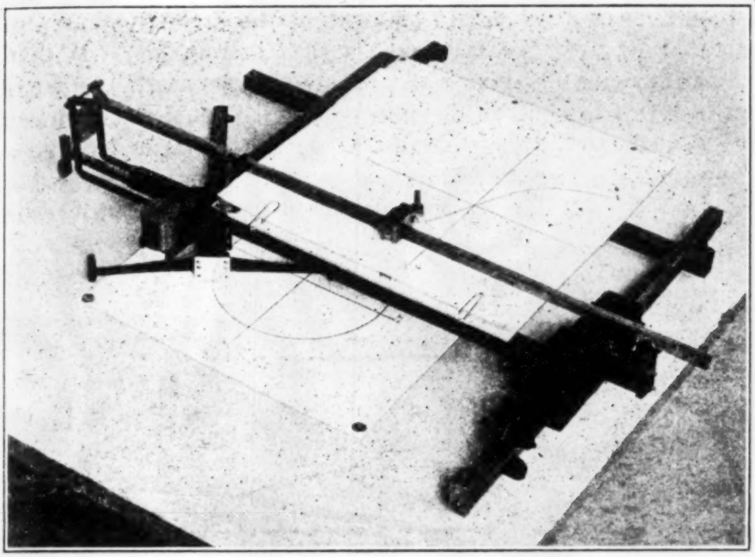
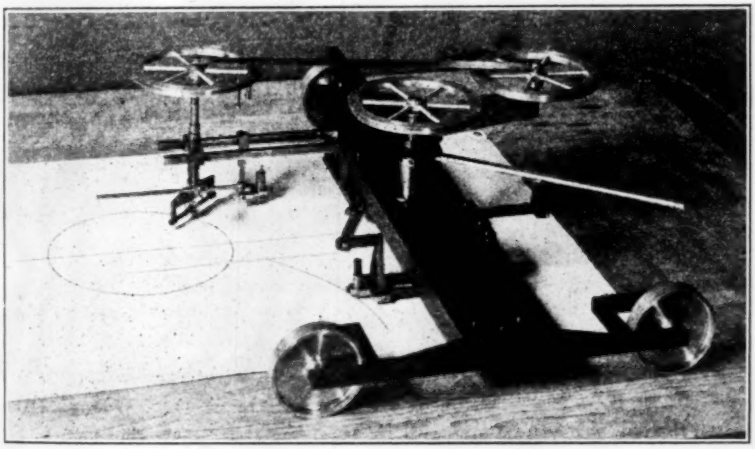
[1] For an illustration of this machine, see the paper by Thomas R. C. Wilson in this Symposium, p. 55.—ED.

[2] For derivation of this equation and further details on the tests made, the reader is referred to the writer's paper, "Stresses in Impact," *Journal of the Franklin Institute*, Vol. 182, p. 771 (1916).

[3] The following articles may be referred to for descriptions of the differentiating instruments:
"A Differentiator," *Scientific American Supplement*, February 12, 1916.
"A Differentiating Machine," *American Mathematical Monthly*, October, 1916.
"Mechanical Differentiation," *Journal of the Franklin Institute*, January, 1918.
"Automobile Performance Analyzed by Mechanical Differentiation," *Automotive Industries*, January 2, 1919.



(*a*) Derivative curve drawn on card mounted on moving carriage. Tangent determined by image in silver mirror.



(*b*) Derivative curve drawn on same sheet with original curve and in any position relative to it. Tangent determined by course of sharp steel disk tracing original curve.

FIG. 2.—Two Types of Differentiating Machines Devised by the Writer.

obtained by "point-by-point" plotting of the derivative curve and then connecting the points plotted with a smooth line. With the machine illustrated in Fig. 2(*a*), the sheet upon which the original curve is drawn (a circle in the illustration) is tacked to the drawing board so that its X-axis is parallel to the horizontal or base groove of the machine. The platen carrying the sheet upon which the derivative curve is to be drawn can move only in the vertical direction.

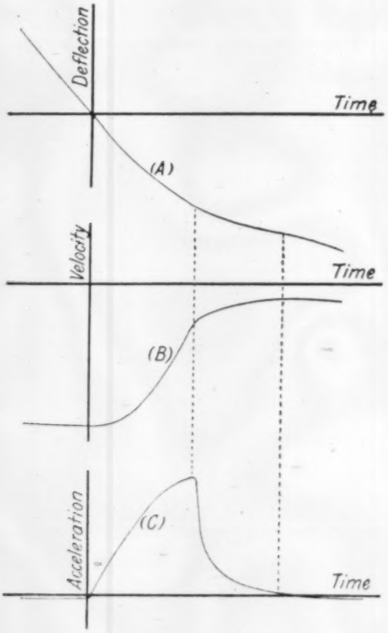


FIG. 3.—(*A*) is a Typical Deflection-Time Curve of a Wood Beam Struck at Center in Impact on Drop Testing Machine.
(*B*) is the Velocity-Time Curve of the Hammer during Contact with the Beam Obtained from (*A*) by Mechanical Differentiation.
(*C*) is the Acceleration-Time Curve Obtained by Mechanically Differentiating (*B*).

The small silver mirror shown with its center on the circle is first rotated until it is perpendicular to the X-axis of the original curve. It is then moved back and forth in this position with the result that the X-axis of the derivative curve is drawn on the platen. The desired derivative curve is then plotted point by point by shifting the mirror and rotating it until the image and the original curve form a smooth continuous line without a cusp at their junction. The mirror is then perpendicular to the curve and by applying pressure to the recording pencil a point on the derivative curve is plotted. With a little practice considerable skill and speed is acquired and the entire derivative curve is plotted in a few minutes.

A typical deflection-time curve is shown as curve *A* in Fig. 3. It must be borne in mind that the time interval during which the impact deflection is being drawn on the sensitized paper is exceedingly small, usually being less than $\frac{1}{30}$ second and in some tests less than $\frac{1}{100}$ second. There should be no slippage and the line drawn by the stylus must be clear and sharp, for even a very small deviation in the course of the deflection curve will introduce a serious inaccuracy in the final acceleration curve. The latter is, of course, obtained by first operating on the deflection curve to obtain the velocity curve *B* and then operating on this curve to get the acceleration curve *C*. After substituting the appropriate scale constants the scale of curve *C* in feet per second per second is obtained and the acceleration can be substituted in Eq. 1. The deflections corresponding to each acceleration are then plotted against the forces computed from Eq. 1, yielding the desired force-deflection curves shown in Fig. 4.

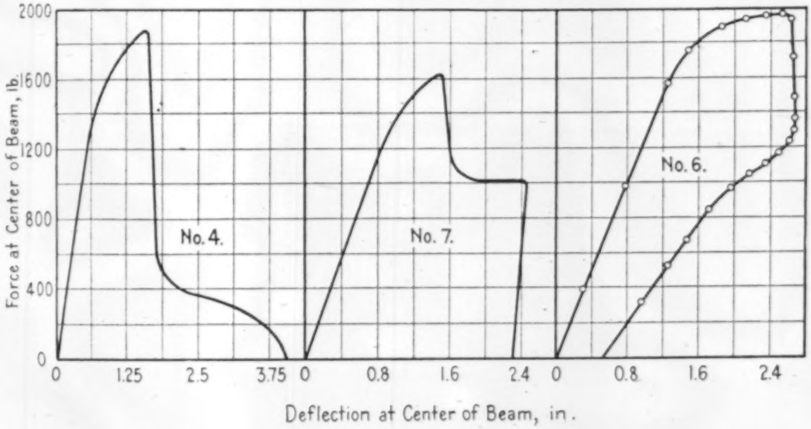


FIG. 4.—Representative Impact Load-Deflection Curves of Wood Beams Struck at the Center.

The three curves of Fig. 4 were selected because they represent failures of various types. In No. 4 failure is complete and the corresponding deflection, velocity, and acceleration-time curves are about as shown in Fig. 3. At maximum or failure load there was a sudden rather violent rupture which apparently left only a small portion of the fibers intact. The latter then failed progressively as the hammer continued in its downward course. Only part of the total kinetic energy of the falling hammer was required to rupture this beam. The hammer continued downward after the beam had been completely broken through.

Beam No. 7 suffered a partial failure at maximum load and then after deflecting another inch it broke again, rupturing all but a few fibers. The failure consumed almost the entire energy of the hammer. Those fibers which remained unbroken at maximum deflection possessed sufficient strength to bring the hammer to a stop. Final collapse occurred just as the hammer stopped, and the beam possessed barely enough strength then to return the hammer upward a small distance.

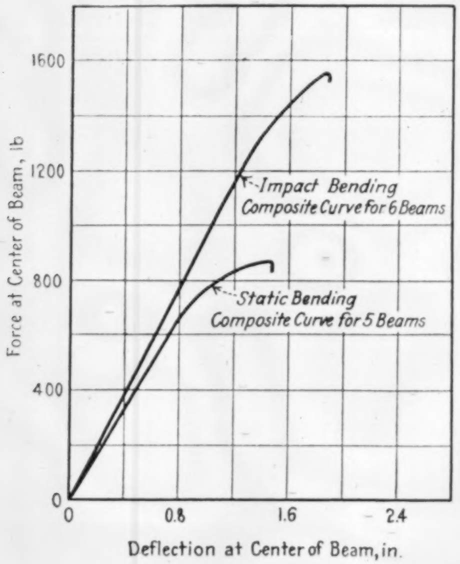


FIG. 5.—Composite Load-Deflection Curves of Wood Beams of the Same Size Struck in Impact and Loaded Statically.

Beam No. 6 showed a pronounced yielding before any of the fibers tore in tension, possibly due to compression of the top fibers. After the first or initial failure, which occurred at the maximum load, there was a very slight increase in the deflection followed by the return of the hammer upward. The area included by the loop in the force-deflection curve represents the energy consumed by the beam. The area under the return curve represents the energy reintroduced into the hammer on receding. The difference in the slope of the straight-line portion of the upper and the lower curves is, of course, due to a change in section of the beam caused by failure of some of the fibers. It would be a simple matter to compute from this curve the effective section of the partially ruptured beam by means of the deflection formula for simple beams loaded at the center.

In addition to giving a record of the progress of failure under an impact blow, the method outlined also throws some light on the time-relation of the changes that take place in a failing beam. The points on the curve for beam No. 6, Fig. 4, space off equal time intervals. In this case the time between two successive points was 0.00167 second.

After plotting the load-deflection curves for each beam under impact as well as in static loading, a composite curve for each method of testing was drawn. These curves are shown in Fig. 5. The number of tests made was, of course, very limited. They indicate a slightly greater modulus of elasticity in impact loading. It does not seem that the elastic properties of wood should be appreciably affected by rate of loading. Possibly a finer deflection-time curve would yield slightly different results showing more nearly a straight line to failure, in which case the two curves would practically coincide at small loads. The curves actually obtained show an elastic limit under impact twice as large as the elastic limit under static bending. This relation between impact and static bending elastic limits substantiates the same conclusion based on the repeated impact test made by the Forest Products Laboratory.

The method of determining forces in impact here outlined is also applicable to metals if the specimens are not made too long so that vibration waves will be set up. For this purpose a drop test is preferable to pendulum impact because the means for getting a graphical record of deflection are more readily applied in the drop test. The impact force-deflection curve in this case would throw light on the progress of the failure with respect to time and deflection and a new view of brittleness or toughness might be established. Wires and sheets could be tested by suddenly stretching them under impact, and their behavior during the sudden loading could be seen in graphical representation.

As a routine or shop test the analytical procedure described would be impractical. The skill of an experienced investigator is required to operate the differentiating machines and to obtain accurate deflection-time curves, as well as to interpret the results. As a means of investigating the phenomenon of failure of wood, metals, and other comparatively tough materials under impact blows the method described is believed to open up new avenues of information.

MEASUREMENT OF THE FORCE OF IMPACT BY MEANS OF THE ELASTIC STRETCH OF A STEEL BAR.

By H. F. Moore.[1]

Some time ago the writer was called on to make an experimental study of the tensile strength of certain grades of steel under very rapidly applied loading,—loading completed in a few hundredths of a second. In making this study load was applied to specimens by means of a falling weight, and the load was measured by the elastic stretch of a steel bar, the stretch being measured by a simple recording extensometer.

The arrangement of testing machine and extensometer is shown in Fig. 1(*a*) and (*b*). The specimen *S* is held in sockets K' K''. The upper socket K' is attached to the bar *T* whose elastic stretch measures the tensile load. The upper end of the bar *T* is attached to the framework of the machine. The bearing between the bar *T* and the plate at the top of the machine is spherical-seated, to minimize bending stresses in the bar. The lower socket K'' is attached to the pull rod *R*. The weight *W* slides freely over the pull rod. As shown in Fig. 1(*a*), the weight *W* is raised and held by the latch *L* attached to the cross bar *C*. When the latch is released the weight falls until it strikes the plate *P* at the end of the pull rod *R* which, together with the specimen *S* and the tension bar *T*, is subjected to a sudden tensile stress.

The apparatus for recording the stretch of the tension bar is similar, in principle, to the stremmatograph invented by Dr. P. H. Dudley and developed in connection with the Investigation of Stresses in Railroad Track,[2] conducted by Prof. A. N. Talbot. As applied to the measurement of stretch under impact of the tension bar, the arrangement of parts of the recording extensometer is shown in Fig. 1(*b*). Near the upper end of the tension bar *T* are fastened two bars B' B'' which extend along opposite sides of *T*. At their lower ends these bars carry needle bars N' N'', which, in turn, slide in bearings in the cross piece *A*. These needle bars carry clamps Q' Q'' in which are fastened phonograph needles; these phonograph needles bear against the face of pieces of glass G' G'' which are very lightly smoked

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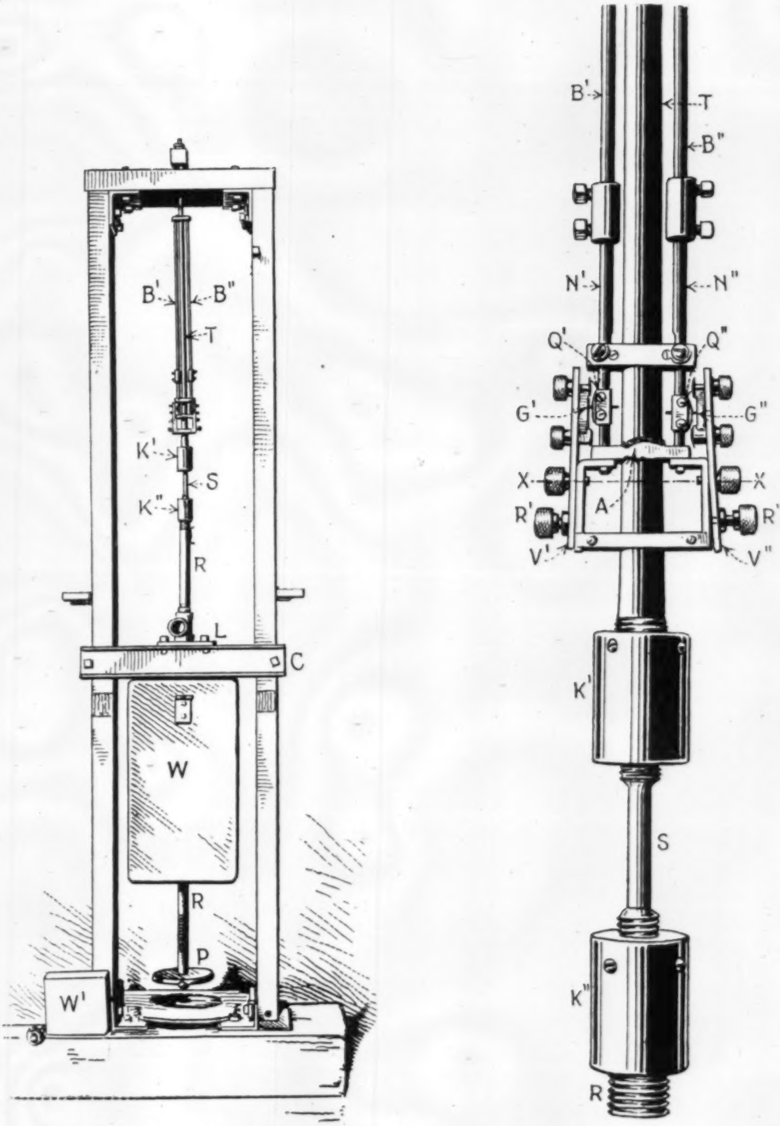
[2] *Transactions*, Am. Soc. C. E., Vol. LXXXII, p. 1225 (1918); *Proceedings*, Am. Ry. Eng. Assoc., Vol. 19, p. 904 (1918).

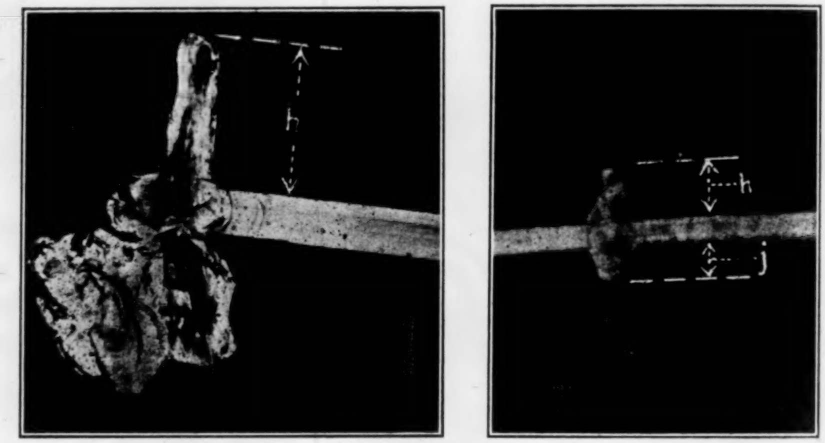

B'
B"
T
K'
S
K"
R
L
C
W
R
P
W'
B'
T
B"
N'
N"
Q'
Q"
G'
G"
X
X
A
R'
R"
V'
V"
K'
S
K"
R

(*a*) Testing Machine. (*b*) Enlarged View of Recording Extensometer.

FIG. 1.—Testing Machine and Recording Extensometer.

with the smoke of burning gasoline. These plates of glass are clamped to plates V' V'', which can be turned about the axis XX when the clamp screws R' R'' are loosened. When the tension bar T is stretched by the sudden tension caused by the impact of the falling weight W, the phonograph needles trace short vertical lines on the smoked-glass plates G' G''. The average length of these lines is a measure of the stretch of the tension bar T, and hence of the tensile load on the specimen. Before allowing the weight W to fall the plates V' V'' are turned slightly about the axis XX and the needles draw short arcs on the smoked glass.

Fig. 2(*a*) and Fig. 2(*b*) show records made in tests with the machine. They are micrographs with a magnification of about 200 times. Fig. 2(*a*) is from the record of a test to rupture. The height h measures the stretch along one side of the tension bar. The average of h and the corresponding value on the record for the other side of the bar gives a measure of the tensile load on the specimen. As the specimen breaks, the tension in the tension bar is suddenly released, and there is set up a "rebound" in compression, shown by the blurred part of the diagram below the horizontal line. The blurring of this part of the record was caused by sidewise motion of the rods B' B'', and the height of the diagram is not affected by this sidewise motion. Fig. 2(*b*) shows a diagram taken in a test in which the specimen was not broken. As before, the amount of tensile load on the specimen is



(*a*) Specimen Broken. (*b*) Specimen Not Broken.

FIG. 2.—Micrographs of Records Made in Tests with the Machine Shown in Fig. 1 (× 200).

proportional to the height *h*, while the height *j* shows the compressive load due to the "rebound" of the tension bar.

The relation between the stretch of the tension bar and the load applied to it was determined by loading the bar in an ordinary testing machine, and at various loads measuring the stretch of the bar by the heights of the smoked-glass diagrams drawn by the apparatus. The height of the smoked-glass diagrams in all tests was read by means of a microscope fitted with a micrometer eyepiece, using a magnification of 75 times.

The effect of inertia of parts of the recording apparatus was minimized by making all such parts as light as was found consistent with rigidity. The effect of inertia, and, in a rough way, the effect of impact loading as compared with static loading, was studied by comparing the height of diagram under static load in a testing machine with the height of the "rebound" diagram when that static load was suddenly released by the breaking of a tensile specimen. In all cases the height of the "rebound" diagram was slightly less than the height of diagram under static load, indicating that inertia of parts did not have any very great effect.

SIGNIFICANCE OF THE IMPACT TEST.[1]

By F. C. Langenberg[2] and N. Richardson.[3]

Many attempts have been made to correlate the impact test, particularly the notched bar impact test, with other tests, and it is of course obvious that the discovery of a definite relation between the static tension test and dynamic impact test would be of great practical value. It does not appear that any such relation can be clearly seen at the present time, and it is very doubtful if much advance will be made until a greater knowledge of the phenomena of impact is available. The application of photo-elastic studies to the determination of the concentration of stress around various types of notches is undoubtedly going to materially assist in the final solution of the problem.

Much attention has been given by able investigators to the comparing of the amount of energy absorbed by specimens of a given material when ruptured under static and dynamic conditions. A. Cornu-Thénard has made a series of very careful tests on similar material tested both statically and dynamically under conditions as nearly identical as possible, with the exception of the speed of applying the load. He concluded that the mechanism of rupture is essentially the same in static and dynamic tests, and that the successive phenomena leading to rupture in the notched bar test are essentially the same, regardless of the speed of application of stress.

A number of investigators have attempted to develop a relation between the amount of work done on a given material when broken statically and dynamically. The conclusions are diversified, but taking into account the more recent work and certain experiments which have lately been carried out by the authors, it is believed that the proper conclusion, in the light of our present knowledge, is that this relationship will vary with the nature of the material undergoing comparison.

Of the five steels recorded by Cornu-Thénard, in one class of steel, he has shown that the energy absorbed in the static test is 81 per cent of the energy absorbed in the same material under dynamic test, whereas in another class it is 108 per cent. This comparison was made on notched bars supported at each end. It is the experience of the authors that there are other classes of material in which the energy absorbed under static conditions is considerably greater than that under dynamic conditions.

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[1] Prepared in Metallurgical Laboratories, Watertown Arsenal, and published by permission of the Chief of Ordnance, United States Army.

[2] Metallurgist, Watertown Arsenal, Watertown, Mass.

[3] Research Engineer, Watertown Arsenal, Watertown, Mass.

A low-carbon steel was recently tested which gave results strongly supporting the statement made above. The Charpy tension specimen was employed, and notched in the usual manner. When this material was broken in the static test the elongation across the notch was approximately 175 per cent, whereas when broken under impact the elongation was only 30 per cent. The fracture in the first instance was amorphous, and a considerable reduction of area occurred, whereas in the second instance the fracture was distinctly crystallin with a very slight reduction of area. The amount of energy absorbed by one of these bars when fractured under static conditions was decidedly greater than the amount of energy absorbed when under impact. When broken under impact, the complete phenomenon of fracture occurred within 0.0005 second, whereas when broken in the static machine the total time under stress was over 60 seconds. Two distinct types of fractures resulted under the two different conditions of testing. The deformation of the crystals which must result when a specimen is deformed under test is apparently dependent upon a time element. When the stress is applied with great rapidity the internal deformation of the crystals apparently does not have time to take place, the result of which is a crystallin fracture with less elongation when under the conditions set forth above.

Regardless of the type of impact machine employed or the form of specimen used, the essential result furnished is the amount of energy absorbed by a specimen in undergoing rupture or a certain deformation. It is therefore obvious that in drawing any comparisons between static and dynamic tests the same essential data must be recorded in both cases. In the ordinary tension test as it is carried out today these data are not recorded, and it is therefore impossible to draw any definite relationship between the values usually recorded in the tension test and the data obtained from the impact test. In the ordinary tension test there are recorded: the elastic limit, the ultimate strength, the total elongation over a specified gage length, and the reduction of area. The elastic limit and tensile strength as conventionally reported are based upon the original diameter of the specimen, and do not represent the actual load carried by the fibers undergoing stress. Furthermore, the elongation is reported as the total elongation after fracture, and it is impossible to determine from the usual data the fiber stress at any given elongation after the elastic limit has been passed.

In order to develop the amount of work done on a tension test specimen as tested in the customary static machine, it is necessary to plot the stress-strain curve, not only up to and slightly beyond the elastic limit, but completely through the entire cycle of the test until rupture occurs. If the complete stress-strain curve is plotted, the area under this curve will represent the amount of energy absorbed by the specimen. In order, therefore, to compare the results of the impact test with any of the data conventionally reported in the tension test, it is necessary to select from this latter information those units which will bear the most direct relationship to the energy absorbed by the piece. It is evident that the elongation is such a factor, since Work = Force × Distance. With one factor only in such an equation, namely distance or elongation, and with the force as a variable factor, it is very obvious that the elongation could not be expected to give any systematic relationship or give any definite idea as to the energy which would be absorbed by a given material, either under static or dynamic conditions. In a like manner, the tensile strength and elastic limit constitute two points only on the stress-strain curve, and do not give any accurate idea of the shape and extent of the entire curve.

It would therefore appear obvious that it is impossible to expect any definite relationship to appear when any of the factors customarily determined in the static tension test are plotted against the results obtained on the notched-bar impact test. The attempt to seek such a relationship, as indicated above, resolves itself into plotting factors which do not define completely the work done in a static tension test against a factor which is a total measure of the work done in a dynamic test.

Several years ago the policy was inaugurated in the laboratories at Watertown Arsenal of testing four transverse notched Charpy specimens from every forging from which a tension test was taken. These parallel tests were run on all classes of steel, both in the annealed and heat-treated condition, and were taken as a matter of routine from forgings which were to be placed in service of various kinds. These data are too voluminous to include in this report, but it can be stated quite definitely that the elastic limit and tensile strength plotted as a function of the work done on the Charpy specimen give not the remotest idea of any existing relationship. In plotting the elongation of the tension specimen as a function of the result of the

Charpy test, about the only conclusion that can be drawn is that when the elongation of the tension specimen is very low the work done on the Charpy specimen will be low, but it does not follow that when the elongation of the tension specimen is high the Charpy value will be correspondingly high.

A very striking example of the failure to ascertain from the results of the static tension test the shock resisting properties, or more properly expressed, the ability of a specimen to absorb energy under impact, is demonstrated in the results given in Table I, which illustrate the improvement of shock properties upon quenching certain steels from the drawing heat.

TABLE I.—SHOWING THE IMPROVEMENT OF SHOCK PROPERTIES UPON QUENCHING CERTAIN STEELS FROM THE DRAWING HEAT.

Test No.	Chemical Composition. (Values in per cent.)							Static Tension Tests.				Charpy Tests.	
	C	Mn	P	S	Si	Ni	Cr	Elastic Limit, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Transverse, ft-lb.	Longitudinal, ft-lb.
							CHROME-NICKEL STEEL						
1	0.37	0.46	0.045	0.022	0.126	2.97	1.08	103 433	128 970	22.0	55.5	1.50	2.36
2	0.37	0.46	0.045	0.022	0.126	2.97	1.08	98 117	125 450	22.0	64.7	12.74	28.00
							NICKEL STEEL.						
3	0.36	0.72	0.040	0.024	0.215	3.48	....	79 375	104 075	24.25	61.0	....	4.26
4	0.36	0.72	0.040	0.024	0.215	3.48	....	76 000	103 825	24.00	63.5	....	20.31

HEAT TREATMENT.

No. 1. Heat 1000° C. 6 hr., air cool; heat 800° C. 6 hr., furnace cool; heat 825° C. 3 hr., oil quench 6 min.; heat 615° C. 3 hr., furnace cool.

No. 2. As test No. 1 with following additional treatment: Heat 605° C. 1 hr., water quench.

No. 3. Heat 825° C., water quench; heat 650° C. furnace cool.

No. 4. Heat 825° C., water quench; heat 650° C., water quench.

As will be noted, the chrome-nickel steel forging was given, first, a double anneal, quenched in oil from 825° C., and then drawn at 615° C., the forging being furnace cooled from the drawing temperature. The results of the test on this forging are given under test No. 1, and show a Charpy value of 1.5 ft-lb. when the bars were taken in a transverse direction, and 2.36 ft-lb. when the Charpy bars were taken in a longitudinal direction. (The terms "transverse" and "longitudinal" refer in this case to the direction in which the bars were taken from the forging and not to the method of testing, the bars in all cases being the customary square Charpy bar notched in the center and supported at both ends.) The forging was then reheated to 605° C., which was 10° C. lower than the previous drawing temperature, and quenched in water from this temperature. The elastic limit dropped approximately 5000 lb. per sq. in., and the tensile strength approximately 3000 lb. per sq. in., whereas the elongation was unaffected. The reduction of area was increased approximately 9 per cent. The Charpy value on bars taken in the transverse direction was increased eight times, and on bars taken in the longitudinal direction, approximately twelve times.

A similar case on a nickel-steel forging is shown in tests Nos. 3 and 4. Again it will be noted that the quench from the drawing heat made very little difference in the ordinary tensile properties, whereas the Charpy value on bars taken in the longitudinal direction was increased five times. An inspection of these data will show that none of the tensile properties bear any simple or definite relation to the values obtained in the impact test.

TABLE II.—TESTS FROM A CHROME-NICKEL STEEL FORGING WHICH FAILED IN SERVICE.

Condition.	Static Tension Tests.					Charpy Tests.		
	Elastic Limit, lb. per sq. in.	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Transverse, Notched, ft-lb.	Tensile, Notched, ft-lb.	Tensile, Unnotched, ft-lb.
TEST BARS TAKEN IN LONGITUDINAL DIRECTION.								
As received	104 000	109 750	136 500	19.2	51.2	2.14	5.93	166.1
Quenched 800° C., drawn 575° C.	105 000	109 000	135 833	18.2	48.1	2.81	12.55	174.3
Quenched 800° C., drawn 650° C.	93 000	96 333	120 833	20.6	54.6	11.04	14.91	175.2
TEST BARS TAKEN IN TRANSVERSE DIRECTION.								
As received	85 000	97 000	119 350	3.3	5.7	1.37	2.01	4.36
Quenched 800° C., drawn 575° C.	100 000	104 666	130 250	6.3	7.6	2.30	4.32	77.67
Quenched 800° C., drawn 650° C.	92 000	94 666	119 500	15.6	34.0	4.57	7.64	169.10

Another significant example which can be cited is that of a certain chrome-nickel steel forging which failed in service. This forging was thoroughly tested after its failure, with bars taken in both the longitudinal and transverse directions. A section of the forging was then heated to 800° C., quenched in water, drawn at 575° C., and cooled in the furnace. A similar complete set of test bars was taken after this treatment. Another section of the forging was quenched in water from 800° C., drawn at 650° C. and cooled in the furnace. A similar set of test bars taken in both the longitudinal and transverse directions was taken after this treatment operation. The results given in Table II represent the mean of from four to eight individual tests. Referring to the bars taken in a longitudinal direction, the material as received from service showed excellent qualities, with the exception of the notched impact specimens, which were exceedingly low, giving values comparable to cast iron. After the material was requenched and drawn at 650° C. the elongation and reduction of area were only slightly improved, accompanied by a reduction in the elastic limit and tensile strength. The results, however, on the Charpy specimens, both transverse and tensile, were most decidedly improved.

Referring next to the bars taken in a transverse direction, the elongation and reduction of area were very low in the condition as received from service, as were also the results of the Charpy notched specimens, both transverse and tensile. After the forging was quenched and drawn at 650° C., the elongation and reduction of area were decidedly improved, as were also the results of the Charpy specimens, both notched and unnotched.

In these cases, the static results of both longitudinal and transverse specimens are available, but even under this rather unusual condition it is impossible to develop any definite relationship between these results and the values obtained on the notched impact specimens. It is obvious, however, from the results, that low elongation and reduction of area, even in one plane of a forging, will result in low values being obtained on notched impact specimens. Although this general observation has been made in many cases, it does not follow that good ductility in all planes will invariably be associated with a high energy absorption on notched test bars broken under impact.

In order to offer further opportunities of comparison, Table III is submitted, which shows the results obtained upon testing certain pieces of ordnance of both foreign and domestic manufacture, including somewhat unusual steels. One set of bars was taken longitudinally, or in the direction of the major axis of the forging, and another set of bars was taken tangentially, or in a transverse direction to the major axis of the forging. The tabulated results are the mean of from two to eight individual tests. Attention is invited to the fact that the elongation on the longitudinal specimens varies from 21.5 to 26 per cent. The work absorbed by the transverse Charpy specimens varies from 3.05 to 33.38 ft-lb. On the specimens taken in a transverse direction the elongation varies from 8.5 to 25 per cent, and the energy absorbed by the transverse Charpy bars from 2.76 to 21.54 ft-lb. An elongation of 21.5 per cent on one set of specimens corresponds to an energy

TABLE III.—TESTS OF ORDNANCE OF FOREIGN AND DOMESTIC MANUFACTURE.

From	Component.	End.	Direction of Taking Specimens.	Chemical Composition. (Values in per cent.)								Static Tensile Properties.					Brinell Number.	Charpy Tests.		
				C	Mn	P	S	Si	Ni	Cr	W	Elastic Limit, lb. per sq. in.	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.		Transverse, ft-lb.	Tensile, Notched, ft-lb.	Tensile Unnotched, ft-lb.
German 77-mm. Gun	Jacket	Breech	Longitudinal	0.23	0.35	0.022	0.014	0.185	5.75	0.02	0.28	65 000	70 600	98 250	22.5	54.6	196	22.86	15.21	126.70
	"	"	Transverse	0.23	0.35	0.022	0.014	0.185	5.75	0.02	0.28	61 250	68 000	95 350	21.5	53.3	196	21.54	.....	117.62
German 105-mm. Howitzer	Jacket	Breech	Longitudinal	0.51	0.20	0.009	0.032	0.275	3.14	1.49	....	.....	76 750	101 300	26.0	62.3	210	18.07	24.02	177.11
	"	"	Transverse	0.51	0.20	0.009	0.032	0.275	3.14	1.49	....	60 000	78 950	107 100	19.5	49.1	210	18.69	19.97	173.90
German 150-mm. Howitzer	Jacket	Breech	Longitudinal	0.35	0.28	0.033	0.057	0.255	2.68	1.13	....	64 380	73 740	98 430	22.8	59.1	200	23.96	18.25	147.73
	"	"	Transverse	0.35	0.28	0.033	0.057	0.255	2.68	1.13	....	65 000	71 750	96 730	18.8	46.1	200	16.32	17.80	131.15
German 150-mm. Howitzer	Breech Block	.....	Longitudinal	0.69	0.27	0.026	0.038	0.245	....	....	....	55 000	62 650	106 350	21.5	43.3	206	3.05	6.32	96.30
	" "	.....	Transverse	0.69	0.27	0.026	0.038	0.245	....	....	....	51 250	58 100	103 450	17.8	32.4	206	2.76	9.55	151.21
German 150-mm. Gun	Tube	Muzzle	Longitudinal	0.47	0.32	0.030	0.036	0.220	3.04	1.55	....	65 000	69 000	111 550	22.8	53.3	229	30.25	24.78	172.63
	"	"	Transverse	0.47	0.32	0.030	0.036	0.220	3.04	1.55	....	80 000	88 750	111 500	9.0	22.7	229	11.85	15.47	71.30
German 150-mm. Gun	Tube	Breech	Longitudinal	0.46	0.36	0.030	0.038	0.165	3.02	1.53	....	64 250	73 630	106 480	24.6	62.3	211	33.38	22.66	171.18
	"	"	Transverse	0.46	0.36	0.030	0.038	0.165	3.02	1.53	....	60 000	70 580	104 000	15.3	27.1	211	15.07	14.71	119.00
German 150-mm. Gun	Jacket	Muzzle	Longitudinal	0.37	0.16	0.035	0.049	0.225	3.04	1.23	....	70 000	73 500	98 680	23.2	55.3	192	27.21	11.07	151.94
	"	"	Transverse	0.37	0.16	0.035	0.049	0.225	3.04	1.23	....	68 000	73 660	97 530	8.5	19.1	192	18.06	18.74	106.77
German 150-mm. Gun	Jacket	Breech	Longitudinal	0.37	0.19	0.033	0.048	0.190	2.97	1.14	....	69 000	72 560	96 060	24.3	60.4	194	28.41	20.37	149.81
	"	"	Transverse	0.37	0.19	0.033	0.048	0.190	2.97	1.14	....	65 000	70 790	94 310	18.9	34.6	194	19.65	17.30	107.21
German 150-mm. Gun	Breech Ring	Muzzle	Longitudinal	0.44	0.29	0.032	0.052	0.218	2.87	1.26	....	70 750	75 630	102 310	23.6	56.5	206	26.26	19.09	141.51
	" "	"	Transverse	0.44	0.29	0.032	0.052	0.218	2.87	1.26	....	69 500	73 750	98 750	11.5	22.2	206	18.79	21.83	120.45
U. S. 240-mm. Howitzer No. 29	Tube	.....	Longitudinal	0.41	0.67	0.037	0.032	0.128	2.72	0.07	....	.....	66 670	101 500	22.7	46.4	192	22.60	17.42	164.4
	"	.....	Transverse	0.41	0.67	0.037	0.032	0.128	2.72	0.07	....	.....	64 670	100 340	22.8	46.2	192	15.33	16.76	164.9
U. S. 240-mm. Howitzer No. 48	Tube	.....	Longitudinal	0.40	0.59	0.040	0.030	0.135	3.16	0.16	....	.....	60 340	101 000	25.3	49.9	195	16.39	17.09	167.0
	"	.....	Transverse	0.40	0.59	0.040	0.030	0.135	3.16	0.16	....	.....	65 000	100 000	25.0	43.3	195	12.34	12.98	152.6
U. S. 240-mm. Howitzer No. 28	Tube	.....	Longitudinal	0.45	0.71	0.039	0.032	0.195	3.67	0.04	....	69 380	75 130	108 250	22.8	57.2	217	9.51	11.90	147.45
	"	.....	Transverse	0.45	0.71	0.039	0.032	0.195	3.67	0.04	....	73 750	79 230	108 560	17.3	33.5	217	5.64	12.26	110.34

absorption of 3.05 ft-lb., whereas on another set of specimens an elongation of 21.5 per cent is comparable to an energy absorption of 21.54 ft-lb. It is believed that a careful analysis of these data will substantiate the general conclusions advanced in the body of this paper, that it is impossible to draw any definite relationship between the results of the static tension test as conventionally recorded and the results of the impact test, regardless of the direction in which the test bars are taken from the forging.

In view of what has been stated in the previous portion of this paper, the question might logically be asked: What property or properties of various materials does the impact test reveal? It is believed that this question can be answered quite definitely as follows:

The impact test reveals the amount of work which must be done on a given specimen in order to produce rupture or a certain deformation. In the usual tension test, if the elastic limit is determined the engineer can safely apply this result in figuring the dimension of any member of a structure. In the case of the impact test, the results cannot be so applied. The work required to break any given section cannot be calculated from the work required to fracture a test bar of different dimensions. This does not, however, destroy the value of the impact test. Its comparative value is still vital in passing upon the properties of a given material for certain specific purposes.

The above statements are based upon results obtained from notched test bars broken as beams, supported, as the case may be, at one or both ends. It may not represent conditions for notched tension tests, but sufficient data are not yet available to make a definite statement regarding this point.

How then can the results of the impact test be interpreted in engineering practice? This can probably best be answered by the following illustration. No component of a gun, such as the jacket or tube, which has ruptured in service from a cause which cannot definitely be assigned to defective ammunition, excessive powder pressure, etc., has shown an impact value exceeding 6 ft-lb. on specimens tested in a small Charpy impact machine. It has therefore become the practice of Watertown Arsenal to take impact tests from all components of a gun and, regardless of their ordinary tensile properties and the acceptability of the forging as judged from this test, no piece is accepted unless the results on the small Charpy impact machine show a value of at least 6 ft-lb. In order to have a factor of safety, no major forging would be accepted unless this result was at least 10 ft-lb. It is believed that for any class of service a careful study of failures, together with material which is satisfactory, will enable the determination of a critical impact value for a specific service.

Although not necessarily pertinent to the subject under discussion, it is undoubtedly a fact that many metallurgists and engineers question the value of the impact test on either notched or unnotched specimens. It has been the experience of the laboratories at the Watertown Arsenal that the Charpy impact test has materially assisted in the diagnosis of many failures of parts in service, and has made possible the prevention of their re-occurrence when applied to the testing of replacement parts. Although no definite relationships exist between the static tensile properties as conventionally used and the results of the Charpy tests, this in itself cannot condemn the Charpy test or any other form of impact test on either notched or unnotched bars. Many specific cases could be cited where the impact test has been of the utmost practical value, and in view of this condition it is not believed that condemnation of the test is justified.

DISCUSSION ON IMPACT TESTING.

Mr. Farmer. MR. F. M. FARMER.—Committee D-9 on Electrical Insulating Materials is interested in impact tests in connection with molded insulating materials but it is not in position to contribute anything of a constructive nature to the Symposium. On the contrary, it is seeking information.

The committee's problem is apparently a comparatively simple one, namely, the use of a type of test which will indicate the approximate relative performance of different materials under conditions the character of which is similar to those encountered in service. Probably the single-blow type of impact test approaches most frequently the conditions found in service, namely, the occasional blow received by the material during the mounting of metallic parts, installation, etc. Of course, there are many electrical applications where the insulating parts are subjected to repeated and continuous blows.

It is probable that any one of several of the types of impact testing machines that have been developed could be used for testing insulating materials. It was hoped by the committee, however, that this symposium would indicate the possibility of standardizing on one type of machine which our committee could also accept for molded materials.

Mr. Hatt. MR. W. K. HATT.—The record here ought to show, I think, more in detail, the development of impact tests. The first machine with which the speaker experimented was a machine for impact tension, and the specimens used were 8 ft. long and about $\frac{1}{3}$ in. in diameter, of various kinds of metals. There was an upper testing head and a lower tup. The three objects were raised together, the upper head, the specimen and the hammer. When dropped, and the upper head came in contact with shoulders of the guides, the hammer went on and broke the specimen. With a rotating drum and tuning fork, a displacement-time curve some 8 or 10 in. long, in some cases, was obtained, from which the force which was pulling the specimen, the kinetic force, was computed and shown on diagrams in comparison with the static stress-strain curve. The object of course was to find out if there was some particular brittleness, or quality of steel producing brittleness, which would be detected by a so-called impact test, though not by a static test. When we came to compute the rate at which that bar was stretched in impact tests in comparison with the rate at which it was

Mr. Hatt. stretched in the static test, the speed of stretch seemed quite low, and not in the same degree as the capacity of metals to transmit stress. The question is raised as to what is an impact test, what is the speed of deformation that separates a fast static test from an impact test. I recollect that one Scandinavian experimenter produced a tension break of metals by exploding gunpowder between two heads. He determined a very large difference of energy required to break as between an impact and a static test.

The *Proceedings* of the Society contain a paper on "Tensile Impact Tests of Metals," in which various grades of metals were used and the static and impact test compared. The effect of temperature on the results, determined from the temperature of a solution of carbolic acid, snow and ether, which is perhaps 90 or 100° F. below zero, up to a temperature of some 400° F., the effect of different forms of specimens, and also the effect of different numbers of blows required to produce rupture, was determined. One phase of this work which was particularly interesting was that wherever there was a difference in the homogeneity of the metal, the impact test developed several necks in the bar so that a bar which was broken by several blows would have the appearance of one of those old fashioned bedsteads. There seemed to be shown one difference between the static test and the impact test in the development of the successive necks of stretch and hardness when the speed was great.

Then finally, Mr. Turner built a machine which is called here the Hatt-Turner machine, for compression and flexure in which be used the device of a magnet for lifting the weight, and this offered, of course, a very easy and simple release. That machine was used mainly for bending, since the main part of the impact tension test seemed to have been served. Some work was done on concrete in compression and bending impact.

My recollection is that for normal materials there was practically no difference between the work required to break a specimen in the slow testing tension machine and the impact test, again remarking that the speed of stretch was very low in each case, very much below the capacity of metal to transmit stress throughout its mass.

Something has been said about tests of wood. I hope that in the discussion Mr. Wilson will perhaps speak of ball tests as applied to wood and tell us whether a ball test applied to wood is not as good an index of general quality as the more expensive tests which are now made. There is a very interesting comparison between wood and concrete in several respects, namely, the effect of the speed of tests upon the results, wood and concrete both being plastic under long time

Mr. Hatt. loads, and both showing a higher elastic limit under quickly applied loads; both being hydroscopic and both being affected by the temperature at which they are tested. I suppose all those three things are merely expressions of colloidal structure.

Mr. Fry. MR. L. H. FRY.—I desire to call attention to a form of impact testing which is required in some of the specifications of the Society, but which has not been referred to in the Symposium: namely, the proof testing of full-sized axles and shafts. Proof tests are required for carbon-steel and for alloy-steel axles and shafts when quenched and tempered. The axle is supported on pillow blocks 3 ft. apart, on a standard A. R. A. drop test machine, and is struck by a tup of 1640 lb. weight, the height of fall being found by dividing the cube of the axle diameter in inches by 100. Thus, an 8-in. axle receives a blow from approximately 5 ft. 3 in., so that the striking energy is about 8400 ft-lb. It is the intention of this test to bend the axle so as to produce a stress of approximately 80 per cent of the elastic limit. Now it is a simple matter to calculate what energy is required to bend an axle to that amount. With an 8-in. axle it is found that to produce a maximum fiber stress of 40,000 lb. per sq. in. with supports 3 ft. apart, a central load of 223,000 lb. is required. The corresponding deflection is 0.036 in. If the axle is carried on rigid supports and if there is no crushing either on the supports or where the load is applied, the energy required for bending is about 335 ft-lb. Now in the drop test, the striking energy of the tup is 8400 ft-lb., about 25 times the energy necessary for the bending of the axle. At first sight, it is not easy to understand how the axle takes up this energy without being greatly overstrained. To try to get some light on this subject, I made some experiments some time ago by placing calibrated copper plugs under the pillow blocks supporting the axle. A number of plugs were cut from a 1-in. bar, about 1 in. in length, the ends squared and the length carefully measured. Some of the plugs were calibrated by being submitted to a drop test to ascertain the relations between the compression and the amount of energy absorbed. Other plugs were calibrated by compression under a testing machine to ascertain the relations between the compression and the maximum pressure applied. Then similar plugs were placed under each pillow block supporting the axle, and the axle submitted to the proof test. On an 8-in. axle, with 8200 ft-lb. of striking energy in the tup, the compression of the plugs corresponded to about 3200 ft-lb., or 40 per cent of the striking energy. The axle had taken up and transmitted to the anvil practically 8 times the energy required for the flexure which would stress the outer fiber to its elastic limit. This is evidently due to the conditions under which

Mr. Fry. impact occurs. As the tup comes in contact with the axle, the pressure on the axle rises, the axle is accelerated downward, it presses on the anvil and starts acceleration of the anvil downwards. This action takes place before the maximum pressure of the tup on the axle is reached, and consequently there is a considerable amount of work done in accelerating the axle and the anvil before the maximum pressure is reached. A comparison of the compression of the plugs under the axle with the compression calibration under the testing machine indicated that the maximum pressure obtained on the axle is close to that required to test the axles to 80 per cent of their minimum elastic limit.

This is a brief survey, but it is hoped it may indicate the direction in which further tests may be made with advantage.

Mr. Wilson. MR. T. R. C. WILSON.—I may say, in reply to Mr. Hatt's suggestion, that we have made for many years at the Forest Products Laboratory, a ball test on wood as one of our standard tests. This test is modeled after a test devised by an Austrian investigator named Janka. It is a measurement of the force required to imbed a ball of a certain diameter into the surface of a piece of wood. I have not studied in detail the relation between the results of this test and the results obtained under impact tests of beams. However, we have studied rather carefully the relation between the specific gravity of wood and each of these tests, and there is an indication of a general correlation between the impact and the ball test through the fact that the results of each of those tests are related to the specific gravity of wood in about the same manner. I am quite certain, however, that the ball test will not bring out the same properties as the impact bending test does with sufficient accuracy to permit its substitution for the latter.

Mr. McAdam. MR. D. J. MCADAM, JR.—It seems to me very important that results as well as methods of measurement of stresses produced by impact be given consideration at this Symposium. I should therefore like to ask what data are available with regard to the ratios of elastic limit and ultimate stress under impact to the static elastic limit and ultimate stress of metals? Do these ratios vary with the toughness of the material? It seems to me that data on these ratios, as well as on the ratio of impact resilience to static resilience, would enable us to determine the relative value of impact and static tests on notched bars in detecting brittleness of materials. It would enable us to determine whether or not the sensitizing effect of the notch overshadows any sensitizing effect of speed of application of load.

Mr. Goldbeck. MR. A. T. GOLDBECK.—There is a very simple and most ingenious device for measuring impact pressures that has been described by

Mr. Goldbeck.

Mr. H. Kreüger of Stockholm in a bulletin of the Engineering Science Academy of Stockholm, Sweden, entitled "Method for Measuring and Calculating the Magnitude of Forces with Particular Regard to Impact Forces." The method is exceedingly simple. (See Fig. 1.) There is a very hard polished steel surface, and a very hard, polished steel ball. The surface is coated with lampblack; the impact is delivered to the steel ball, which is thereby deformed elastically, and a circular mark is produced on the steel surface where the ball has been pressed into contact. Then it is simply a question of measuring the diameter of the mark produced on this polished steel surface. The device is calibrated in a testing machine under static load so that the diameter of the circular marking may be expressed in terms of pressure.

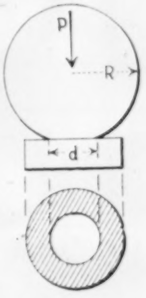

FIG. 1.

It would seem that such a device should measure impact pressure with the introduction of very little error due to the cushioning effect of the instrument.

Mr. Smith.

MR. E. B. SMITH.—In the papers presented only a few methods have been presented which may be used for measuring the force of impact. There are a few other methods which I believe should be mentioned, but in order that we may more fully understand the fundamentals on which impact testing must be considered, I wish to discuss briefly some of the usual conceptions regarding impact.

Usually when we think of the force of impact or of some method of measuring it, it is in terms of energy. A little consideration will show that this is in no way an indication of the force of impact. Perhaps a simple analogy will help in making this point clear. Suppose we have a pipe of rather small diameter filled with water to a depth of several feet. We can easily determine the pressure at the bottom of the pipe. Suppose also we have a pan of rather large horizontal area and in this pan is the same amount of water as we had in the pipe but, of course, of much less depth. Now, in the pipe and in the pan we have the same amount of water, yet the pressure at the bottom of the two containers certainly is not the same. Likewise, we may have a small mass of known weight dropping from a known height. This mass possesses a certain amount of energy which may be measured in foot-pounds. Also, we may have a heavy mass of known weight dropping from a lesser height which may possess the same amount of energy, but even though these two masses strike a third mass at different times, they will not produce the same force of impact as measured in pounds nor produce the same effect upon this third body.

Mr. Smith. Before making any extended study of the question of impact, it is absolutely necessary that we realize that the force or pressure of impact can not be measured in terms of energy, and certainly an energy measurement of impact can not be used in designs involving the strength of materials. We must realize that the force of impact is a function only of mass and acceleration. It does not depend upon the velocity of movement of the mass but upon the change in velocity when the mass collides with another body and causes impact. In other words, it is the result of a mass being brought to rest within a certain time. The force of impact is obtained from our old familiar fundamental equation in physics, which is simply: "Mass times acceleration is equal to force."

It is easy to determine the value of the mass but in practical determinations of the value of impact it is usually quite difficult to determine the value of acceleration. Acceleration is the result of bringing the mass to rest within a certain distance or within a certain space of time, and this happens so quickly that it is very difficult to obtain a reliable measurement or indication of its value. It should be noted that in the case of impact or collision between two bodies, the acceleration has a negative value and is commonly called deceleration.

In a paper presented before this Society last year,[1] the speaker described in detail two methods of determining the pressure or force of impact in pounds and not in foot-pounds. The space-time method is probably the only method which may be used to determine accurately what the pressure of impact is. This method requires an autographic curve obtained from the falling body recorded on a moving drum or strip of paper, this curve showing at any instant the relation between distance and time. The second derivative of this curve with respect to time gives the value of the deceleration at any point. Then, knowing the weight of the body and therefore its mass, we find the force of impact by multiplying mass times acceleration.

It is true that this is a very involved and laborious method but after a little experience in the use of these curves in connection with a special micrometer having points or knife edges, or with microscopic scales, very reliable results may be obtained. The practical use of this method, however, is probably confined to laboratory and research work and can not very readily be extended for use in practical commercial work.

Another method for determining the force of impact, which has often been proposed and which has been used to some limited extent,

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[1] E. B. Smith, "Measurement of Impact," *Proceedings*, Am. Soc. Test. Mats., Vol. 21, p. 1073 (1921).

Mr. Smith.

is known as the deformation method, whereby a copper cylinder is interposed in the impact system in such a way as to receive the full force of impact. The amount of deformation of this copper cylinder is an index of the pressure which it has received. This method requires considerable caution in its adaptions and use because the introduction of this copper cylinder into the system introduces a cushioning effect and reduces very materially the force of impact from what it would have been had not this cushioning effect been interposed.

At this point I wish to make a statement concerning the use of the crusher gage. This gage has been used in ordnance work for the purpose of determining the pressure within guns due to powder explosions. The indication from such gages, which depend upon the deformation of a small copper cylinder, is probably correct and accurate under the conditions of use. The small copper cylinder within the crusher gage is subjected to the direct pressure of the explosion within the gun chamber. There is no cushioning effect in this case as the pressure produced within the gun chamber is the result of a gas pressure and is not the result of a mass and an acceleration or deceleration. In this case we have pressures only to deal with and the indication of the crusher gage is direct; but in the case of the use of the copper cylinder or deformation method of determining the force of impact when a moving mass is concerned, the indication as given by the copper cylinder deformation is not a direct comparison with that of an exactly similar copper cylinder under static pressure.

The problem of determining the force of impact will be very greatly simplified when there has been developed a reliable and efficient accelerometer, an instrument which may be attached to a moving mass or hammer in such a way as to indicate the value of the maximum acceleration or deceleration. Some experimental work has been done on these instruments and they seem to give very reliable results. They depend upon the principle of deflection of a rather stiff spring which carries a known weight. When the instrument which carries this spring and weight is in uniform motion with its velocity neither increasing nor decreasing, there is no change in the compression of the spring, but when the instrument experiences changes in velocity, either positive or negative, there results a change in the compression of the spring. Means are provided for measuring this spring compression, and by a calibration of the spring, a constant may be developed for the instrument, which will enable us to determine the acceleration or deceleration experienced by the instrument; since the instrument is attached to the known weight or hammer, it also indicates the acceleration or deceleration of this weight.

Mr. Smith. Another attempt has been made to develop an accelerometer which does not use a spring for the indicating device but which depends upon the action of a quartz crystal supporting a weight, the quartz crystal indicating the pressure produced upon it by means of its Piezo electric effect.

Another point which I wish to mention is that the form of the specimen used in impact tests undoubtedly has a great influence upon the results, because the cushioning effect at the instant of impact between the specimen and the hammer has a vital effect on the resultant deceleration of the hammer and a consequent change in the actual force of the blow. This statement applies also to the kind of material of which the specimen is made; these different materials, because of their hardness and surface resilience, even though the form of the specimen be the same, will offer different resistances to the impact of the hammer. The machines used in making impact tests must take this fact into account, and have a means of measuring the force in pounds rather than in foot-pounds.

As to the effect of impact pressures on materials, we actually know very little. The effect or result is undoubtedly influenced by the speed of application of the force; that is, whether the hammer strikes quickly or slowly, even though the force of impact in pounds may be the same. The character of stress introduced in materials will undoubtedly vary considerably, depending upon whether the material is brittle and hard or whether it is ductile and soft. The higher the velocity of application of the impact pressure, the more nearly will be the effect of producing a pure shearing stress rather than any of the other simple stresses, such as bending, tension or compression.

In conclusion, after an examination of the literature on the subject of impact, we find that there have been very few authors who have gone into the subject in a fundamental way and analyzed all the factors of the problem. It is surprising to note that very few authors have realized the simple fundamental relations in mechanics as they apply to impact problems and it is for this reason that I believe this Society is amply justified in making a thorough study of this subject. It may perhaps be necessary at first to study the subject of impact in an academic way, having in mind, of course, always its practical application; but if we do no more than study it in an academic way, the practical application, after a full appreciation of the subject has been obtained, will immediately present itself

The President. THE PRESIDENT (MR. C. D. YOUNG).—There is general interest in the matter of a deformation method. I did some work some years

The President. ago in connection with obtaining the dynamic augment of driving wheels on a locomotive. As you all know, a locomotive at speed, due to the unbalanced force of the driving wheels, causes a hammer blow on the track. It was our desire to measure the amount of that blow, and where it occurred in reference to the position of the crank pin on the driving wheel, and to check the different mathematical formulas for counterbalancing the reciprocating parts of the locomotive. A very simple scheme was devised of passing a piano wire between the carrying wheels of the locomotive and those of the locomotive testing plant, with the locomotive moving at constant speed; and by nicking the tire opposite the crank pin that same nick developed on the flattened wire as it passed between the wheels, so that one could locate deformation in the wire with reference to the crank pin. Then, by measuring with micrometer calipers the thickness of the deformed wire, it was possible to obtain a check for the dynamic augment formula of the force delivered by the unbalanced locomotive driving wheels.

The plan was very simple and effective. It settled a much mooted question which had been trying railway engineers for a good many years, and was so simple and clean cut that I think the Society should recognize for all time the deformation method wherever it can be practically applied.

Mr. Breyer. MR. F. G. BREYER.—I hope that any committee appointed to study impact will construe impact testing broadly and include all tests in which the rate of application of load is greater than that of the normal testing machines. I know in the case of zinc alloys that impact testing, as commonly understood, lost out, and accelerated rates of loading by other methods won a distinct victory in the analysis of the properties of zinc and zinc alloys with low percentages of impurities. We thought at one time that the impact resistant properties of these alloys would give vital data, but after we devised a dynamic ductility machine which simply tested the ductility at much higher rates of load application than is normally applied in the case of an Olsen or Ericson type of ductility machine, we found that it was variably accelerated load application and not just impact resistance that gave the helpful data.

Mr. Holz. MR. HERMAN A. HOLZ (*by letter*).—Referring to the various opinions mentioned by Mr. McAdam which exist on the effect of the velocity of the hammer in single-blow impact tests, I do not believe that it is feasible to cover this question by a general statement, claiming either that resilience values are greatly affected by differences in striking velocities or that they are uninfluenced thereby. It seems that this influence is quite different with different metals, and unfor-

Mr. Holz. tunately the variation runs in opposite directions in alloy steels and plain carbon steels.

Batson and Hyde, in their recent book on "Mechanical Testing," page 310, report on some investigations undertaken at the National Physical Laboratory by means of a specially constructed double pendulum impact testing machine in which the striking velocity can be considerably increased by mounting the anvil and specimen on one pendulum and the hammer on another pendulum, both swinging in opposite directions and passing each other at the lowest point of their swings. The results obtained were as follows:

	Striking Velocity, ft. per sec.	Energy Absorbed in Fracture, ft-lb.
Iron	16	20.9
	21½	20.2
	43	10.6
Medium-carbon steel	9	7.5
	20	7.6
	43	7.6
Mild steel	9	29.1
	16	27.7
	20	20.0
	29	14.5
Nickel-chrome steel	9	28.9
	16	31.8
	43	39.3

It will be seen that while the energy absorbed in fracture decreases with higher striking velocities in tests of iron and mild steel, it increases considerably with nickel-chrome steel, and it remains constant with medium-carbon steel. These tests, I believe, show that a general statement to cover this point cannot be made and that conditions vary with different metals and alloys. For all practical routine testing it may be possible to overcome this difficulty by standardizing on a definite striking velocity, say 16 ft. per second, in a manner similar to other mechanical tests where some points of variations have been covered by standardizing on a definite force.

Referring to the variations found in static and kinetic notched-bar tests, the resistance of the metal to impact seeming larger than to slow bending, in a similar manner as found in slow and rapid tensile tests, I believe that the explanation of this phenomenon will be found partly in energy losses during the impact test, but it is mainly due, I believe, to the effect of high temperatures in the impact specimens. It is quite evident, I believe, that heat is produced when the hammer strikes the specimen, and besides this source of heat another source of heat may arise through the very rapid internal friction between the

Mr. Holz.

crystals during deformation. It is possible that the great decrease of resilience at temperatures below 20° C. is due to the absence or reduction of this temperature effect. For this reason it would be very interesting, indeed, to ascertain whether impact resilience and static resilience differ also at the lower temperatures, and if so, whether the ratio is different at these temperatures. The effect of heat would also explain the higher ductility found in impact tension tests.

All tensile tests carried out at high speeds show a higher ultimate strength, yield stress and particularly a higher elongation than tensile tests carried out normally. I am referring to the researches of Professor W. E. Dalby who designed a special machine and photographic extensometer permitting tensile tests up to the breaking point within one second, obtaining at the same time a complete load-extension curve. I believe that research work by means of Dalby's apparatus will yield valuable results, because the field lying between the ordinary slow tensile test and the impact tensile test must be carefully studied.

Tammann calls attention to the different behavior of steel under impact and slow tension at different temperatures. While the resistance of the material to impact decreases rapidly below 20° C., its tensile strength increases below 20° C. Tammann explains this difference of behavior by variation of speed in the formation of the gliding planes of the crystals: "If the formation of gliding planes would be a rapid process, the curves for tensile strength and resilience should run parallel at all temperatures. At those temperatures at which impact resistance is low, there is not sufficient time at the instant of impact to permit the formation of gliding planes. In that case the material offers low resistance to sudden applied forces while its maximum tensile strength and elongation under slowly applied forces is quite high."

Under these circumstances I believe that it will also be very interesting to compare the curves of tensile strength and static resilience at low, normal, and elevated temperatures, for the different metals and alloys.

One point that is still open to considerable research and improvement in impact testing is the dimensions of the specimens and the calculation of the test result based on these dimensions. An extensive investigation on the "Laws Underlying the Notched Bar Impact Test"[1] carried out by Mr. Moser at the Krupp Steel Works at Essen has yielded very interesting results along this line. It would take up too much time to go into the details of this investigation, but I want to outline the scope of the experiments undertaken and their most important results.

Four steels (one of low ductility, two of medium ductility, and one nickel steel of high ductility) were investigated. While the standard

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[1] *Kruppische Monatshefte*, December, 1921.

Mr. Holz. specimen used in Germany is the Charpy specimen 30 by 30 mm. in cross-section by 160 mm. long, with a notch 15 mm. deep, 2-mm. radius, the width of the specimen was varied to 10 mm., 15 mm., 20 mm., 25 mm., 30 mm., leaving the height and the length, and the dimensions of notch unchanged. In the standard specimen, the metal in back of the notch is 15 by 30 mm; the section is therefore 450 sq. mm.

The customary method of calculating the test result is to divide the impact force by the cross-sectional area. Philpot has called attention to the fact that if energy is to be expressed in terms of the linear dimensions of the test piece, it should be the energy per *cubic* centimeter, and the calculation must involve a quantity or dimension depending upon the shape of the base of the notch. The energy per square centimeter is of dimensions corresponding to a force divided by a length, a method of measurement which is not used in technical calculations. The cubic dimensions of that zone of the specimen which is actually affected by deformation and energy should form the basis of calculation of the test results.

These considerations were first mentioned by Schuele and Brunner, at the 1909 Congress of the International Association for Testing Materials, and again discussed at the May meeting, 1919, of the Institution of Mechanical Engineers, London. In Mr. Moser's paper, the results are plotted both against area of cross-section (method now standard) and against cubic dimensions of the zone of activities. It is quite surprising to note that if the width is increased above 20 mm. with the steels of medium ductility, the energy absorbed in breakage by impact decreases. A specimen of 0.40-per-cent carbon steel of 25-mm. width absorbs one-third of the energy of that absorbed by a specimen of the same material of 20-mm. width. A steel containing 0.35 carbon showed the same phenomenon. From these tests it would appear that the same material is resilient in narrow specimens and brittle in heavy sections. Results of the same tests, plotted against *cubic* dimensions of the zone of activity of the tested specimens, yielded perfectly straight line relations between resilience and size of specimens, that is, the resilience calculated in this way is always the same for each material, independent of the width of the sections investigated. If, therefore, the test results are calculated on basis of cubic dimensions of the specimens, this has the important advantage that a definite figure, independent of the width of the specimen, is obtained which is characteristic of each metal—the "constant of energy absorption" of the material, based on its cubic dimensions. Taking the constants of energy absorption as ordinates and the reduction of area as abscissas, a straight line relation exists for the three plain carbon steels investigated. Moser also found that the cubic dimensions of that section of metal which participates, the zone of activity, for a definite notch, are proportional to the width of the specimens of all metals. **Mr. Holz.**

Moser comes to the conclusion that for rapid routine testing, it would be too difficult to determine the zone of activity in each impact specimen. However, he considers the present form of Charpy specimen in which the width is equal to twice the thickness of metal back of the notch as unfavorable to consistent results, if the calculation is based on the cross-sectional area, and recommends that the width should be equal to the thickness of metal behind the notch, preferably 10 by 10 mm. If the cross-sectional area in back of the notch is thus chosen and standardized as 1 sq. cm., then the energy or impact force does not need to be divided by the area, but would be immediately equal to the resilience value. The standard specimen recommended on basis of this investigation would then be 20 mm. high by 10 mm. wide by 160 mm. long with a notch 10 mm. deep with 2-mm. radius, so that the cross-section of the metal to be broken by the impact test would be 10 by 10 mm. It sounds quite plausible that it is of advantage to have a specimen which, instead of being square itself, possesses a square cross-section of metal actually under test.

The measurement of force developed and energy absorbed in impact is completely realized in Amsler's "Universal Tup Machine." The method of measuring the residual energy in this machine has been developed by Mr. Alfred Amsler and can be described in short as follows:

The device of measuring the residual energy of the tup consists of two vertical cylinders in each of which plays a piston without any friction. The first cylinder is let into the base plate in the center between the guides. The second cylinder stands on the base plate outside the guides. The two cylinders communicate with one another and are filled with oil. Each ram stands out of its cylinder, and the one of the first cylinder is protected by a cap on which the tup drops. When the piston in the first cylinder is struck by the tup, the shock is transmitted by oil to the ram in the second cylinder, whereby the counter-weight is thrown up along the guide to a height corresponding to the energy left in the tup after dropping. The height to which the counter-weight rises is read on a scale. The operator standing in front of the device can easily watch it.

A method of measuring the force in impact has been developed by Mr. Pierre Breuil and is described in the *Bulletin* of the Section Technique de l'Aeronautique Militaire, July 30, 1919.

TENSILE PROPERTIES OF STEEL CASTINGS.

By Lawford H. Fry.[1]

This paper puts on record the results of nearly 600 tension tests representing steel castings of the grade currently used in locomotive construction. The tests were made by a group of manufacturers of steel castings as a contribution to the work of the A.S.T.M. and A.R.A. Joint Committee on Specifications for Steel Castings. It was thought that information thus collected would afford a proper basis for a study of the tensile properties to be expected in steel castings for locomotives. Information regarding the proper method of measuring the tensile properties was also sought.

The data were collected and reported on by a committee of which the writer was chairman, the other members being Messrs. H. M. Lewis, Pratt and Letchworth Co.; C. N. Ring, Ohio Steel Castings Co.; J. V. R. Stehman, Birdsboro Steel Foundry and Machine Co.; and J. L. Uhler, Union Steel Casting Co. Experiments were also made and reported by Messrs. J. C. Davis, American Steel Foundries; G. T. Johnson, Buckeye Steel Castings Co.; and B. C. Bakewell, Duquesne Steel Foundry.

The program given to the committee in charge of the work called for:

1. The collection of information regarding the tensile properties of steel castings furnished for railroad service; and

2. Accurate measurement of the relation between extension and load during tension testing, particular attention being given to the true elastic limit.

To meet this program, those interested were requested to carry out the two series of experiments which are described in detail below under the headings "Running Tests" and "Precision Tests."

In the first series, or Running Tests, a pair of test coupons was taken from each of 200 castings. The first of the pair was pulled in the usual manner, while for the second the extensometer method adopted for heat-treated forgings by Committee A-1 on Steel was used to determine the so-called elastic limit.[2] The information thus ob-

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[1] Standard Steel Works Co., Burnham, Pa.

[2] See Standard Specifications for Carbon-Steel and Alloy-Steel Forgings (Serial Designation: A 18 - 21), 1921 Book of A.S.T.M. Standards, p. 148. The method is there described as follows:

"The elastic limit called for by these specifications shall be determined by an extensometer reading to 0.0002 in. The extensometer shall be attached to the specimen at the gage marks and not to the shoulders of the specimen nor to any part of the testing machine. When the specimen is in place tained shows (1) the tensile properties of castings furnished for railroad service; and (2) the relation between the yield point and the elastic limit determined by the method of Committee A-1.

In the second series of tests, the so-called Precision Tests, stress-strain curves were plotted using a Berry strain gage to measure the elongation. The tension bars used were taken from special pads cast for the purpose, other bars being used to measure the tensile properties determined in the usual manner. Seven manufacturers cooperated furnishing 40 pads representing 24 heats of steel.

In laying out the two series of experiments it was intended to have the Running Tests made under conditions equivalent to the best mill practice under railroad inspection, with the Precision Tests representing laboratory research conditions. Taking the two series of tests together, the following conclusions can be drawn:

1. When two tension tests are made from a uniform steel casting the variation in the values found for the tensile strength is not usually in excess of 5 per cent of the value of the tensile strength.

2. If a number of uniform bars are used, some to determine the yield point and others to determine the elastic limit, the values of the yield point are more uniform and more consistent than the values found for the elastic limit. It is evident that the value of the elastic limit is more dependent on the personal equation of the observer and on accidental irregularities in the individual determinations. This is true whether the accelerated extensometer method of Committee A-1 is used or whether the elastic limit is measured from a stress-strain diagram as the proportional limit.

3. The uncertainty in the determination of the elastic limit is largely due to the fact which is shown in the majority of the Precision Tests, that there is no constant proportionality between elongation and stress. In other words the annealed cast steels investigated have no "true elastic limit," but behave as plastic rather than as elastic material.

4. The relation between elongation and tensile strength follows closely a hyperbolic law, that is to say tensile strength multiplied by elongation is a constant.

5. The relation between reduction of area and tensile strength does not follow a hyperbolic law as closely as is the case with the elongation. A fairly good approximation to the relation over a short range of tensile strengths is obtained by assuming that tensile strength multiplied by reduction of area is a constant. The value of the constant must, however, be less for high than for low tensile strengths.

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and the extensometer attached, the testing machine shall be operated so as to increase the load on the specimen at a uniform rate. The observer shall watch the elongation of the specimen as shown by the extensometer and shall note, for this determination, the load at which the rate of elongation shows a sudden increase. The extensometer shall then be removed from the specimen, and the test continued to determine the tensile strength."

6. When yield point and elastic limit by the Johnson and Committee A-1 methods are determined for the same cast steel, greater variations in the individual values are found in the two latter than in the yield point. If average values are taken, the relation is approximately as follows:

Tensile strength	100 per cent
Yield point by drop of beam	50 "
Elastic limit, A-1 method	45 "
Elastic limit, Johnson method	42 "

Detailed consideration of the experimental data follows.

RUNNING TESTS.

METHOD OF TESTING.

The program laid out for these tests provided that each manufacturer should set aside from 50 to 100 bars from castings from which other bars had been originally taken for test in the regular course of business. The bars were to be marked so that the results from the duplicate bars could be compared with the results from the original bars. The original bars were to be tested by the usual method, the tensile strength, the yield point by drop of beam, the elongation in two inches, and the reduction of area being measured. The duplicate bars were to be tested in the presence of a railroad inspector appointed by Mr. F. Zeleny, Chairman of the Sub-Committee on Methods of Testing of the Joint Committee of the A.R.A. and the A.S.T.M. The elastic limit was to be determined by a Berry strain gage by the method adopted by Committee A-1 on Steel,[1] together with the tensile strength, the elongation and reduction of area. It was planned to measure also the yield point as shown by the drop of the beam, but this was not found to be practicable in all cases.

Four manufacturers carried out the tests submitting results from a total of 396 bars representing 198 castings. The castings from which bars were taken included locomotive frames, driving wheel centers, and large miscellaneous castings. All of the castings were, as a result of the first test, accepted for railroad service. The castings were of acid and basic open-hearth steel with tensile strengths running from 60,000 to 92,000 lb. per sq. in. and carbon from about 0.20 to 0.44 per cent. From the conditions under which the test bars were selected it is evident that they represent steel castings of good quality as currently accepted for railroad service.

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[1] *Loc. cit.*

EXAMINATION OF TEST RESULTS.

Tensile Strength.—The first step was to compare the tensile strengths of the two specimens from the same casting. Fig. 1 was prepared for this purpose, the tensile strength of the second specimen (T_2) on which the A-1 elastic limit was measured being plotted as ordinate over the tensile strength of the original specimen (T_1) on which the yield point was determined. If both specimens have the same tensile strength, the point will fall on the line *AA*. To facilitate comparison four other lines have been drawn; *BB* marks a second specimen with a strength 5 per cent and *CC* 10 per cent above the first. Lines *DD* and *EE* correspond to second specimens with strengths respectively 5 and 10 per cent below the first.

It is evident that in the majority of cases the variation between the two specimens does not exceed 5 per cent. Further, it will be noticed that in Fig 1 (*a*) there is a tendency for the strength of the second specimen to be less than that of the first. It is probable that this is due to a lower testing speed having been used for the second specimens. Average tensile strengths for the tests from Works A covered by Fig. 1 (*a*) are given below together with testing machine speed:

STYLE OF TEST.	AVERAGE TENSILE STRENGTH, LB. PER SQ. IN.	SPEED OF TESTING MACHINE, IN. PER MINUTE.	
		TO YIELD POINT.	FROM YIELD TO FRACTURE.
First Bar (drop of beam).........	69 680	0.34	1.28
Second Bar (A-1 elastic limit).....	68 690	0.04	0.34

Yield Point.—In Fig. 2, the values Y found for the yield point by the drop of the beam are plotted in relation to the values T of the tensile strength for the same bars. The lines marked $Y=0.60\ T$, $Y=0.50\ T$, and $Y=0.45\ T$ show the position of points when the yield point is respectively 60, 50 and 45 per cent of the tensile strength. It will be noticed that the relation between yield point and tensile strength is generally quite uniform. Taking all tests, the yield point averages very close to 50 per cent of the tensile strength. Practically all of the castings show a yield point in excess of 45 per cent of the tensile strength.

Elastic Limit by Method of Committee A-1.—Values of this property (E) are plotted in Fig. 3 in relation to the tensile strength (T) for the same bars. It is evident that the average value of this elastic limit is not far from 45 per cent of the tensile strength, and 40 per cent of the tensile strength is a representative minimum value.

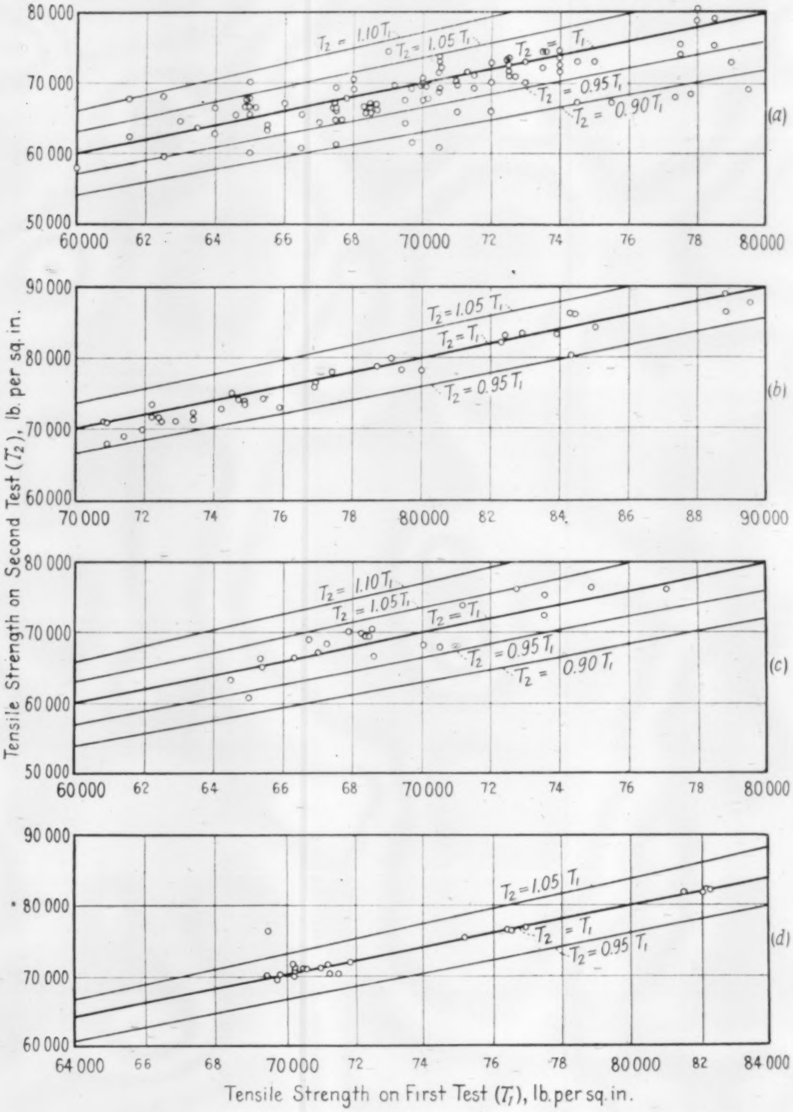

FIG. 1.—Running Tests. Relation between Tensile Strength of Two Specimens from the Same Casting.

The four sections show tests from each of four manufacturers.

The abscissas, T_1, are values of tensile strength from the first series of bars, in which yield point by drop of beam was measured. The ordinates, T_2, are values of tensile strength from the second series of bars, in which the "A-1" elastic limit was measured.

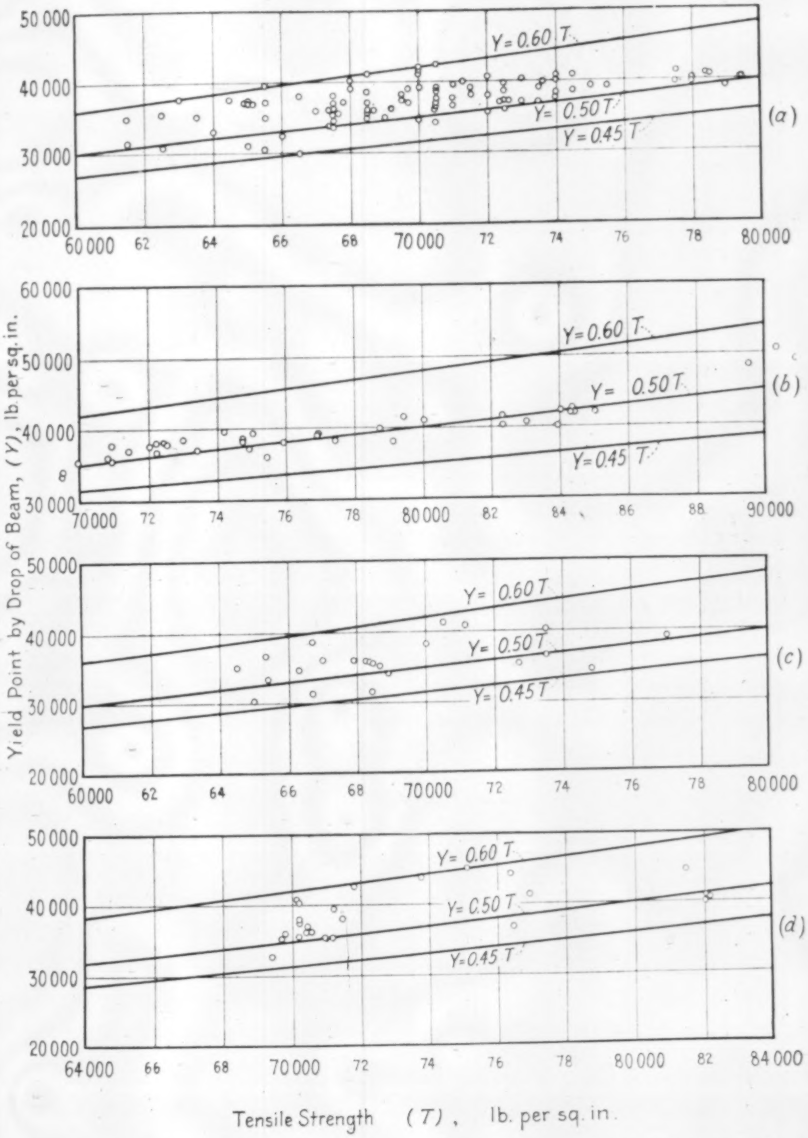

FIG. 2.—Running Tests. Relation between Yield Point and Tensile Strength.

The four sections show tests from each of four manufacturers.

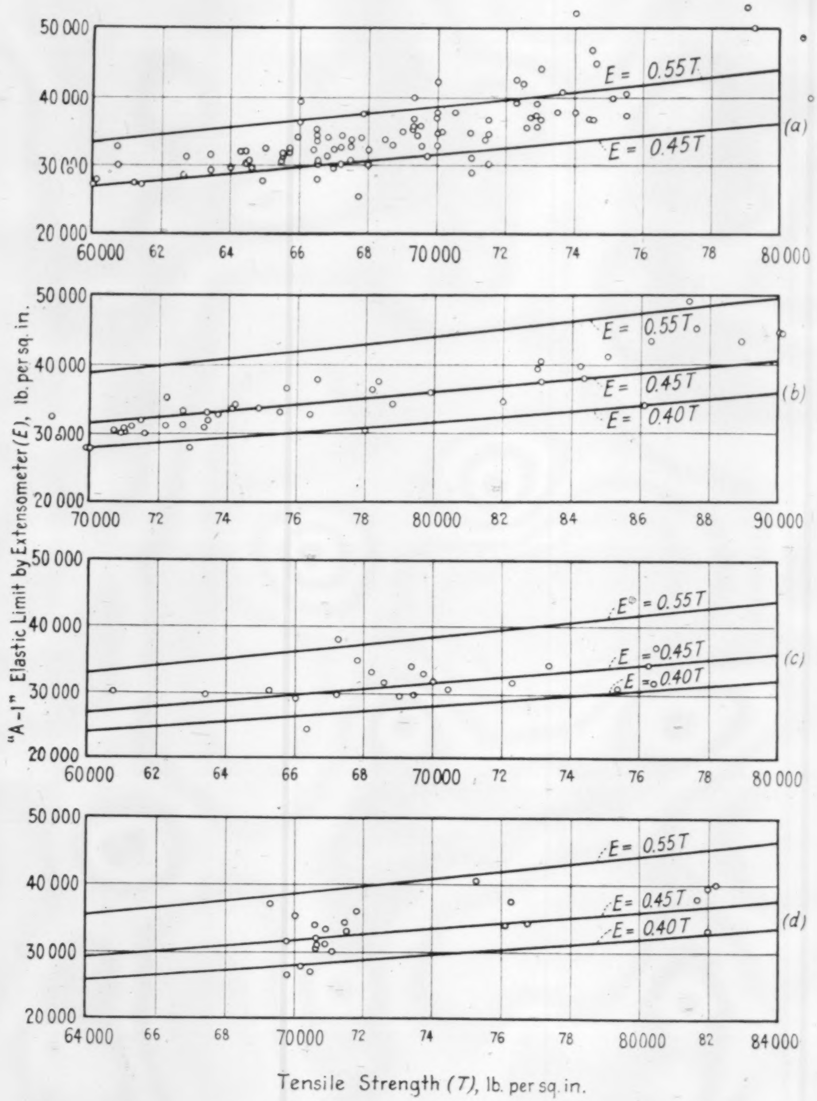

FIG. 3.—Running Tests. Relation between "A-1" Elastic Limit and Tensile Strength.

The four sections show tests from each of four manufacturers.

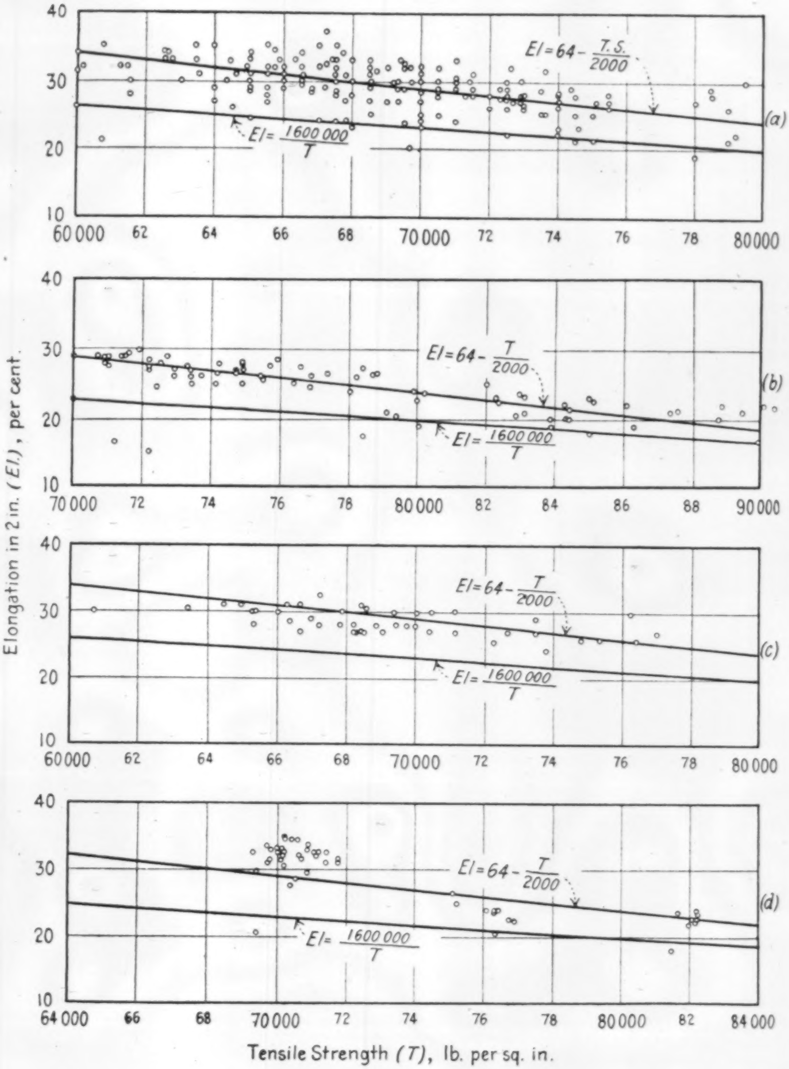

FIG. 4.—Running Tests. Relation between Elongation and Tensile Strength.

The four sections show tests from each of four manufacturers.

A comparison of Figs. 2 and 3 shows that the relation of the A-1 elastic limit to the tensile strength is subject to greater variations than the relation of the yield point to the tensile strength. This greater variation appears to be due to irregularities in the measurements rather than to any irregularity in the steel. Where an abnormal value of elastic limit is found combined with a normal value of yield point, the other properties of the steel do not indicate that the steel is in an abnormal condition. In several cases the value found for the elastic limit is higher than that for the yield point; this can only be accounted for by an error in observation. Determination of the A-1 elastic limit is made by observing the load corresponding to a sudden increase in the rate of motion of the strain gage needle. This change in the motion of the needle is not always clearly marked, and in the decision as to the instant of its occurrence the personal equation of the observer is of importance.

The measurement of the yield point by the drop of the beam is a simpler observation. With steel castings, the drop of the beam is well marked provided the machine is operated at a proper speed, and it is readily observed by both machine operator and inspector. The personal equation of the observer has less influence on the result than is the case with the A-1 elastic limit.

Elongation.—The values found for the elongation (measured in 2 in.) are plotted in Fig. 4 in relation to the tensile strength. As the values from both series of tests (yield point and elastic limit) are plotted in this figure, there are two points for each casting.

It is evident from the plot that there is a general relation between the values of elongation and tensile strength, but that no very exact law can be deduced. In Great Britain it is usual to assume that the relation follows a straight line law; for example, some of the British Standard Specifications require that the tensile strength in tons per square inch plus the elongation in per cent shall be equal to a constant. This is the same as requiring

$$\text{Elongation} = \text{Constant} - \frac{\text{Tensile Strength}}{2240} \quad \ldots\ldots\ldots \quad (1)$$

in which the tensile strength is expressed in pounds per square inch. In this country it is usual to assume that the relation follows a hyperbolic law of the form

$$\text{Elongation} = \frac{\text{Constant}}{\text{Tensile Strength}} \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

With the present data available, an attempt was made to ascertain which form of law best fitted the relation. In each of the plots a straight line has been drawn with the equation

$$El = 64 - \frac{T}{2000} \qquad (3)$$

and a hyperbola with the equation

$$El = \frac{1{,}600{,}000}{T} \qquad (4)$$

The numerical coefficients for these equations were chosen with a view to placing the straight line so as to represent the average values, with the hyperbola to represent the minimum values. It is to be noted that the scales used for plotting the results are such that the hyperbola departs very little from a straight line. It is evident that there is little to choose between the two lines in their representation of the relation between elongation and tensile strength.

Reduction of Area.—The values for reduction of area are plotted in Fig. 5 in relation to tensile strength. As the values from both series of tests (yield point and elastic limit) are plotted in this figure, there are two points for each casting. These plots are very similar to those for the elongation (Fig. 4) already discussed. Here also a hyperbola has been drawn to represent the minimum values, the equation being

$$R = \frac{2{,}600{,}000}{T} \qquad (5)$$

Straight lines have also been drawn aiming at the average values. In Fig. 5 (*a*) a line with the equation

$$R = 84 - \frac{T}{2000} \qquad (6)$$

represents the mean position of the points fairly satisfactorily. In Fig. 5 (*b*), however, a more rapid slope is needed, the equation of the mean line being

$$R = 119 - \frac{T}{1000} \qquad (7)$$

In Fig. 5 (*c*) the same line as given by Eq. 6 gives fairly satisfactory results, though it is somewhat above the mean position, while for Fig. 5 (*d*) an even greater slope than that of Fig. 5 (*b*) is required, the equation being

$$R = 187 - \frac{T}{530} \qquad (8)$$

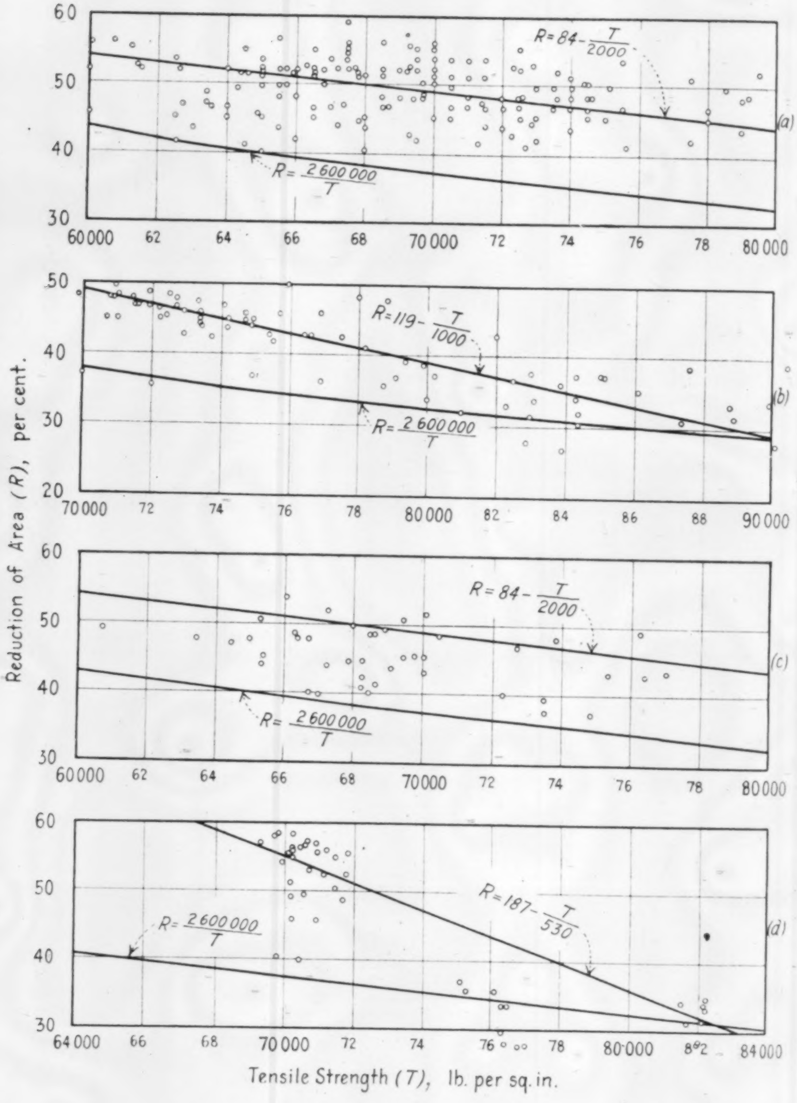

FIG. 5.—Running Tests. Relation between Reduction of Area and Tensile Strength.

The four sections show tests from each of four manufacturers.

It is evident that a single straight line equation of this form will not represent the relation between reduction of area and tensile strength. The hyperbola of Eq. 5 gives better results, though the corresponding values are somewhat high for the tensile strengths over 80,000 lb. per sq. in., which occur in Figs. 5 (*b*) and 5 (*d*).

It is thought that the most satisfactory method of expressing the relation between reduction of area and tensile strength is to use a hyperbolic form of equation with a change in the numerical coefficient according to the range of tensile strengths to be covered. For example, reasonable minimum values are given by the following equations:

For low tensile castings:

$$\text{Reduction of Area} = \frac{2{,}600{,}000}{\text{Tensile Strength}} \quad \ldots\ldots\ldots\ldots (5)$$

For medium tensile castings:

$$\text{Reduction of Area} = \frac{2{,}500{,}000}{\text{Tensile Strength}} \quad \ldots\ldots\ldots\ldots (9)$$

For high tensile castings:

$$\text{Reduction of Area} = \frac{2{,}400{,}000}{\text{Tensile Strength}} \quad \ldots\ldots\ldots\ldots (10)$$

PRECISION TESTS.

METHOD OF TESTING.

The purpose of these tests was to measure accurately the relation between load and extension for cast steel of various grades made by a number of manufacturers, particular attention being given to determination of the elastic limit.

To furnish specimens, each manufacturer was requested to make two pads about 2 in. thick from each grade of cast steel currently made. Each pad was to carry 10 coupons on the pad; the method of their removal and the gating and heading of the pads was left to the judgment of the manufacturers. After removal of a coupon from each end, the pads with coupons were to be annealed.

The coupons were to be numbered from 1 to 10 from one end of the pad to the other and were to be tested as follows:

No. 1............................Remove from pad unannealed.
" 2............................Test for plotting stress-strain curve.
" 3............................Pull regular tension test.
" 4............................Reserve.

No. 5	Reserve.
" 6	Test for plotting stress-strain curve.
" 7	Pull regular tension test.
" 8	Reserve.
" 9	Reserve.
" 10	Remove from pad unannealed.

Standard A.S.T.M. 2-in. tension test specimens were to be used for all tests. The method suggested for obtaining the stress-strain curve was as follows:

Apply Berry Strain gage.
Apply load of 2000 lb. (10,000 lb. per sq. in.). Read gage.
" " " 4000 " (20,000 " "). " "
" " " 5000 " (25,000 " "). " "
" " " 5400 " (27,000 " "). " "
" " " 5600 " (28,000 " "). " "

Continue to increase the load by increments of 200 lb., noting the gage reading after the application of each increment of load, until the yield point as marked by the strain gage is reached. Remove strain gage and pull the specimen as in a regular tension test, noting the tensile strength and measuring the elongation and reduction of area.

Manufacturers were requested to plot the resulting stress-strain curves to uniform scales. Two different scales were chosen to show the effect of a change of scale on the results.

RESULTS OF EXPERIMENTS.

Seven manufacturers cooperated, furnishing forty pads representing 24 heats of steel, acid, basic and electric. The carbon content ranged from 0.24 to 0.48 per cent and the tensile strength of the annealed material from 66,000 to 95,000 lb. per sq. in.

Table I shows the material furnished by each manufacturer and the average tensile properties. Details of the experimental methods of each manufacturer are given below:

Manufacturer A furnished two pads, one from each of two heats of acid open-hearth steel. The test program was followed.

Manufacturer B furnished two pads, one from each of two acid open-hearth heats, of 0.28 and 0.43 per cent carbon respectively. In addition to the two program curves from each pad, curves were drawn from the unannealed bars and from four other annealed bars. On two of the bars the yield point was taken after the increment loading for the curves had been carried out. The suggestion that two bars be pulled in the regular manner to determine yield point only was not followed.

Manufacturer C furnished six pads representing three acid open-hearth heats. The test program was followed.

Manufacturer D furnished twelve pads representing four basic and three electric heats. The test program was followed.

Manufacturer E furnished two pads, one from each of two acid heats. The test program was followed.

Manufacturer F. The pads furnished were not arranged exactly in accordance with the program. Two pads were made from each heat, each pad providing four test bars. For each heat four bars from one pad were pulled in the regular manner determining the yield point, while the other four bars were used to give stress-strain curves. Seven heats are represented, four acid and three basic. The method of obtaining the stress-strain curves was to place the bar in the testing machine and apply a load of 500 lb. Two Berry strain gages were clamped on opposite sides of the bar and set at zero. Loads of 2000,

TABLE I.—PROPERTIES OF STEEL USED IN PRECISION TESTS.

Manufacturer.	Heat No.	Type of Steel.	Carbon, per cent.	Pad No.	Average Tensile Properties.			
					Yield Point by Drop of Beam, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.
A	34 559	Acid O. H.	0.24	1 A	45 500	76 200	27.2	40.0
	34 577	"	0.28	2 A	45 200	75 200	25.5	40.4
B	296 C	Acid O. H.	0.43	1 B	47 700	93 000	19.2	28.6
	313 C	"	0.28	2 B	36 000	72 200	28.3	48.5
C	4558	Acid O. H.	0.30	A	38 100	75 600	26.1	44.5
	"	"	"	B	36 600	73 500	27.7	43.5
	4574	"	0.34	C	36 650	76 500	25.7	39.3
	"	"	"	D	36 700	75 250	26.1	40.0
	4436	"	0.26	E	36 300	68 100	30.0	49.0
	"	"	"	F	36 600	68 300	31.0	49.1
D	8707–4	Basic O. H.	0.25	16	38 700	70 600	34.8	57.2
	"	"	"	14	37 200	70 500	33.2	56.1
	8693–4	"	0.27	8	34 500	71 500	25.8	35.8
	"	"	"	4	35 300	70 000	32.7	55.8
	8154–3	"	0.27	13	40 300	71 100	31.8	54.6
	"	"	"	14	35 400	71 100	31.5	51.0
	9159–1	"	0.33	17	38 300	70 000	32.2	51.5
	"	"	"	15	38 200	70 300	30.9	47.8
	E-1192	Electric	0.35	22	42 500	81 300	21.4	31.7
	"	"	"	25	40 000	82 100	23.0	32.5
	E-1193	"	0.33	18	38 900	76 600	24.3	39.5
	E-1194	"	0.31	19	44 500	76 000	24.0	34.0
E	1144	Acid O. H.	0.24	1 E	37 300	67 600	32.4	53.0
	1161	"	0.26	2 E	36 400	67 400	33.7	54.6
F	37 825	Basic O. H.	0.29	1 F	39 300	74 400	27.8	47.6
	"	"	"	2 F	......	73 100	31.4	54.5
	9424	"	0.25	3 F	35 500	65 800	36.3	59.6
	"	"	"	4 F	......	66 200	32.5	57.6
	49 892	"	0.24	5 F	35 700	67 750	33.1	60.3
	"	"	"	6 F	......	67 900	34.1	59.6
	679	Acid O. H.	0.28	7 F	36 000	74 600	29.4	49.0
	"	"	"	8 F	......	73 000	31.5	50.1
	7244	"	0.29	9 F	37 500	71 500	26.2	38.0
	"	"	"	10 F	......	72 600	27.8	45.8
	836	"	0.29	11 F	35 300	70 200	31.1	49.8
	"	"	"	12 F	......	71 700	26.4	48.0
	114	"	0.30	13 F	38 900	76 400	28.9	45.6
	"	"	"	14 F	......	73 850	31.4	50.0
G	4479	Acid O. H.	0.48	1 G	46 200	95 300	13.0	13.9
	4492	"	0.27	2 G	35 000	71 100	33.0	49.1

4000 and 5000 lb. were placed on bar and readings obtained on both strain gages after each load. The load was then reduced to 500 lb. and strain gages removed and placed on opposite sides of the bar in a plane at right angles to the first plane of setting. Loads of 2000, 4000, 5000, 5400 lb. and increments of 200 lb. thereafter were placed on the bar until the strain gages showed approximately 40 divisions or more. This method of taking reading on four sides of the bar was followed in order to determine if the bar was actually loaded axially.

Manufacturer G furnished one pad from each of two acid heats. The carbon content was respectively 0.27 and 0.48 per cent. As both pads were annealed at the same temperature, the grain condition in the higher carbon was not entirely satisfactory. The test program was not followed strictly. Four bars from each pad were tested in the same manner. The testing machine was run at 0.03 in. per minute, and the Berry strain gage readings noted as the specified loadings were passed. The proportional limit, Committee A-1 elastic limit, and yield point by drop of beam were also noted. The speed of the machine was then increased to 0.125 in. per minute and maintained at this figure until fracture occurred. The machine was thus run without stopping during the test. Tests were also made in the same manner with 41 specimens from locomotive driving wheel centers and frames, and with 8 specimens from similar castings using a speed of 0.125 in. per minute through the yield point and stopping the machine at the load points. Curves were not plotted from the test figures.

DISCUSSION OF RESULTS.

The stress-strain curves plotted from the various experiments afford data for a discussion of the so-called elastic limit of annealed cast steel. Representative curves are given in Figs. 6 to 8.

The term "elastic limit" has been so loosely used as to require definition as a preliminary to any discussion into which it is to be introduced. The American Society for Testing Materials, through its Committee E-1 on Methods of Testing, has defined "elastic limit" as "the greatest load per unit of original cross-section which does not produce a permanent set." In the current testing of steel castings for railroad service, however, this stress is practically never measured or considered. In such work "elastic limit" means either the so-called elastic limit determined by the Johnson "50-per-cent method" or the so-called elastic limit determined by the method of Committee A-1 on Steel.[1] It should be noted that the determination of either of these limits depends on a change in the proportionality between stretch and load. Consequently by the definitions of this Society they are species of "proportional" and not "elastic" limit.

For either of the two "elastic limits" to have a real physical meaning in connection with the steel the stress-strain curve must start as a straight line, showing constant proportionality between load and elongation, and then bend more or less sharply towards a horizontal position. This type of curve is illustrated by Fig. 6 showing the two curves from bars Nos. 2 and 6, pad No. 22, heat No. E-1192, Manufacturer D. These show an almost perfect initial straight line with a break of "elastic limit" at about 38,000 lb. per sq. in. This type of curve is not usual for steel castings, which are better represented by Fig. 7, the curves from pad No. 25, heat No. E-1192, and from pad No. 16, heat No. 8707-4, also from Manufacturer D. In these curves there is no straight-line portion. The ratio of elongation to load increases continuously from the origin. By any rigid definition the material has zero elastic limit. The same indication is shown in practically all of the curves plotted. Curves from four bars from heats Nos. 313-C and 296-C by Manufacturer B are shown in Fig. 8 as further examples. These are drawn with the elongation on a smaller scale than was used in Figs. 6 and 7 and this causes the initial part of the curve to appear more nearly a straight line. If the elongation scale is still further reduced, it becomes possible to draw a straight line which will appear to represent the points fairly closely, and by so doing an apparent elastic limit can be obtained. This procedure,

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[1] *Loc. cit.*

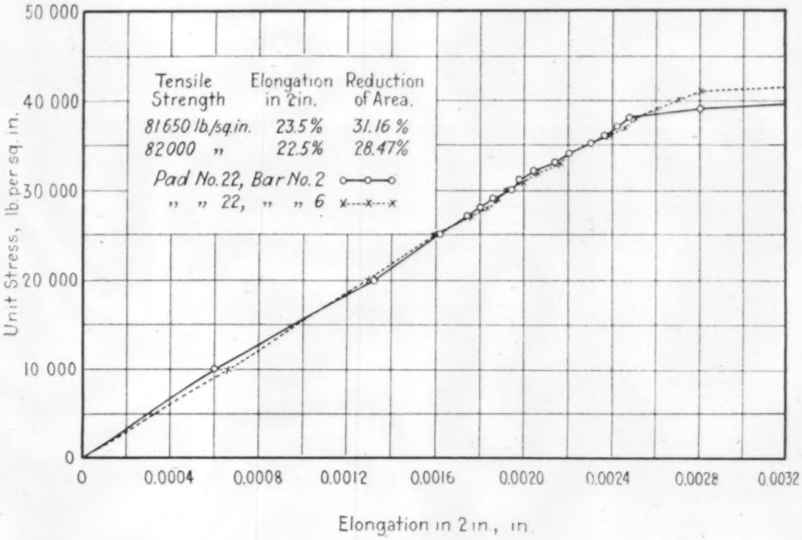


FIG. 6.—Precision Tests. Stress-Strain Curve for Bars Nos. 2 and 6, Slab No. 22, Heat No. E-1192, Manufacturer D.

These curves are unusual for cast steel as they show almost perfect constant proportionality between stress and strain in the earlier portion of the curves. The break from proportionality puts the Johnson elastic limit at 38,000 lb. per sq. in. for bar No. 2 and at 39,500 lb. per sq. in. for bar No. 6.

however, is merely measuring the elongation by a precise extensometer and then plotting so as to eliminate the effect of this precision of measurement. To secure accurate information regarding the properties of the steel, it is necessary to measure elongation and load with precision and to plot them to a scale corresponding to the precision of measurement.

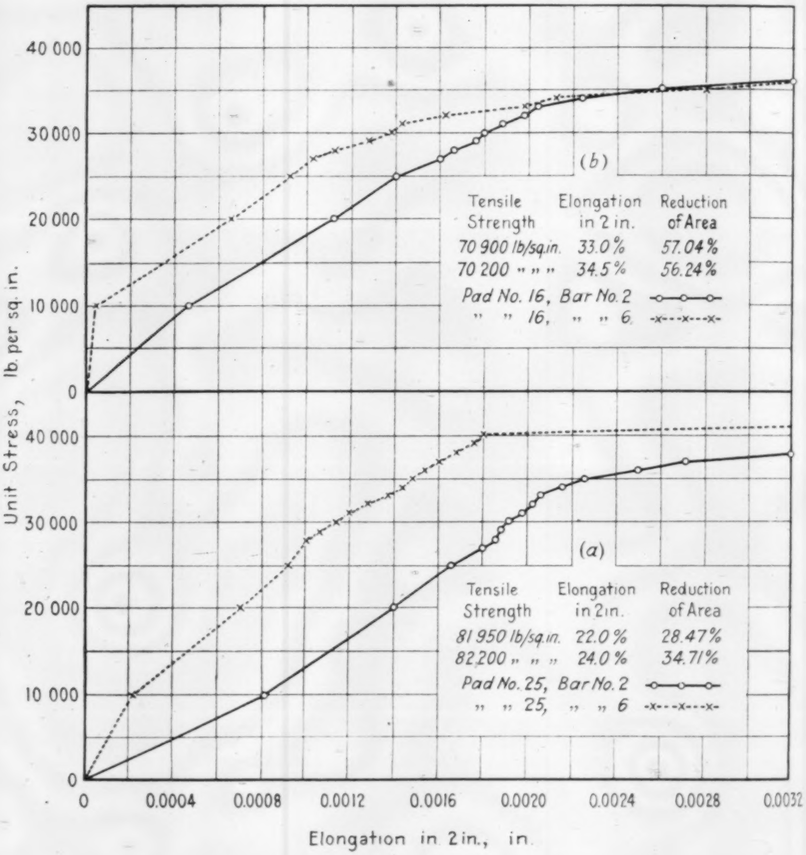
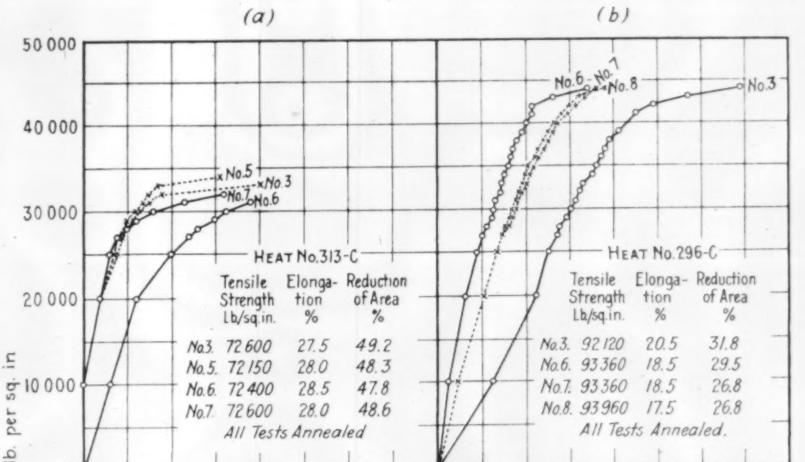


FIG. 7.—Precision Tests. Stress-Strain Curves from Tests of Manufacturer D.

(*a*) Heat No. E-1192, Pad No. 25, Bars Nos. 2 and 6.
(*b*) Heat No. 8707-4, Pad No. 16, Bars Nos. 2 and 6.

The irregular form of these curves is typical of the stress-strain curves from annealed steel castings. It is only in exceptional cases, as shown in Fig. 6, that constant proportionality between stress and strain is found.

The curves plotted from the whole body of tests lead to the belief that a tension specimen of cast steel stretchs irregularly under a gradually increased load. The irregularity is partly due to bending



HEAT No. 313-C

	Tensile Strength Lb/sq. in.	Elongation %	Reduction of Area %
No.3.	72 600	27.5	49.2
No.5.	72 150	28.0	48.3
No.6.	72 400	28.5	47.8
No.7.	72 600	28.0	48.6

All Tests Annealed

HEAT No. 296-C

	Tensile Strength Lb/sq. in.	Elongation %	Reduction of Area %
No.3.	92 120	20.5	31.8
No.6.	93 360	18.5	29.5
No.7.	93 360	18.5	26.8
No.8.	93 960	17.5	26.8

All Tests Annealed.

HEAT No. 313-C

	Tensile Strength Lb/sq. in.	Elongation %	Reduction of Area %
No.1.	69 160	23.0	35.3
No.2.	71 900	29.0	49.2
No.4.	69 500	28.0	44.3
No.8.	71 750	29.0	48.0

Nos. 1 and 4 Unannealed.
" 2 " 8 Annealed.

HEAT No. 296-C

	Tensile Strength Lb/sq. in.	Elongation %	Reduction of Area %
No.1.	93 020	15.0	20.6
No.2.	92 860	20.0	29.5
No.4.	96 020	13.0	15.6
No.5.	92 120	20.0	27.5

Nos. 1 and 4 Unannealed.
" 2 " 5 Annealed.

FIG. 8.—Precision Tests. Stress-Strain Curves from Tests of Manufacturer B.

(*a*) Heat No. 313-C. (*b*) Heat No. 296-C.

Showing the irregular curves typical of annealed steel castings, similar to those in Fig. 7.

of the specimen, but is also largely due to the nature of the material. This conclusion is based on the experiments made by Manufacturer

F with two and four strain gages and on experiments, not reported here, made by Manufacturer D with three strain gages.

The curves reproduced show that the general rule is for the stretch to increase at a slightly greater rate than the load until the yield range is reached. There is then a rapid increase in stretch with a very slight increase in load. It is important to note that there is no

TABLE II.—RELATION OF YIELD POINT TO ELASTIC LIMIT BY JOHNSON METHOD.

Manufacturer.	Heat No.	Pad No.	Yield Point by Drop of Beam.			Elastic Limit by Johnson Method.			
			No. of Bars.	Average Value, lb. per sq. in.	Deviation of Maximum and Minimum Values from Average, lb. per sq. in.	No. of Bars.	Average Value, lb. per sq. in.	Deviation of Maximum and Minimum Values from Average, lb. per sq. in.	Elastic Limit as per cent of Yield Point, per cent.
A	34 559	1 A	2	45 500	± 500	2	29 250	±2 250	64.5
	34 577	2 A	2	45 250	± 750	2	37 000	±1 000	81.5
B	296 C	1 B	2	47 700	± 650	4	43 000	± 980	90.5
	313 C	2 B	2	36 000	± 525	4	31 300	+2 350 −1 350	87.0
C	4558	A	2	38 100	± 2500	2	27 000	± 0	71.0
	"	B	2	36 600	± 125	2	27 000	± 0	74.0
	4574	C	2	36 650	± 50	2	25 500	± 500	69.5
	"	D	2	36 700	± 325	2	26 000	±1 000	71.0
	4436	E	2	36 300	± 300	2	25 000	± 0	69.0
	"	F	2	36 600	± 275	2	27 500	± 500	75.0
D	8707–4	16	2	38 725	± 725	2	30 500	±2 750	79.0
	"	12	2	37 200	± 250	2	33 000	±1 000	89.0
	8695–4	8	2	34 500	± 1875	2	28 500	±2 000	83.0
	"	4	2	35 300	± 75	2	33 500	±3 500	95.0
	8154–3	13	2	40 300	± 2250	2	31 500	±4 500	78.0
	"	14	2	35 400	± 125	2	32 600	±1 625	92.0
	9159–1	17	2	38 300	± 2300	2	34 100	±1 125	89.0
	"	15	2	38 200	± 1925	2	31 250	± 250	81.5
	E-1192	22	2	42 550	± 1185	2	38 750	± 750	91.0
	"	25	2	45 000	± 75	2	36 625	±3 375	91.5
	E-1193	18	2	38 900	± 2125	2	36 000	±1 750	92.5
	E-1194	19	2	44 550	± 450	2	37 250	±3 250	83.5
E	1161	1 E	2	36 400	± 75	2	27 500	± 500	75.5
	1144	2 E	2	37 300	± 250	2	26 000	±1 000	70.0
F	37 825	1 & 2	4	37 300	± 500	4	35 000	+4 300 −5 400	89.0
	9424	3 & 4	4	35 500	± 1000	4	29 450	+1 150 −1 050	83.0
	49 892	5 & 6	4	35 700	± 1000	4	38 450	+5 150 −11 050	108
	679	7 & 8	4	36 000	± 750	4	32 100	+5 600 −4 700	89.0
	7 244	9 & 10	4	37 500	± 500	4	35 950	+5 050 −5 150	96.0
	836	11 & 12	4	35 300	+ 450 − 300	4	35 800	+ 975 −1 025	101
	114	13 & 14	4	38 900	+ 325 − 700	4	39 650	+3 050 −3 850	102
G	4479	1 G	4	46 200	+ 650 − 1400	4	40 225	+2 275 −2 925	87.0
	4492	2 G	4	35 000	+ 700 − 450	4	31 600	+ 350 − 650	90.0

Average (excluding Manufacturer F) .... 84.5 per cent.

definite point of inflection marking the change from the so-called elastic range to the yield range. In other words, the stress-strain curves do not show any definite stress, before the yield range is reached, at which a physical change affecting the strength of the material takes place. Precise measurement and plotting of the stress-strain curve fails to determine a "true elastic limit" for cast steel.

The yield range marks a change in the strength of the material, and as such requires critical attention. In the light of the information given by the curves, the Johnson 50-per-cent elastic limit method is seen to be an arbitrary method of determining a point near the beginning of the yield range. The yield point as determined by the drop of beam marks a point at which the yield is well developed. In round figures the total stretch in the 2-in. specimen is between 0.001 and 0.002 in. for the Johnson limit and between 0.01 and 0.02 in. for the drop of beam. This applies to the cast steel specimens, and, other things being equal, the stretch for either of the points in question will be greater in proportion to the tensile strength.

TABLE III.—COMPARISON OF VALUES OF JOHNSON ELASTIC LIMIT AND YIELD POINT.

Manufacturer	Heat No.	Pad No.	Bar No.	Johnson Elastic Limit, lb. per sq. in.	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Fig. No.
D	E-1192	22	2	38 000	......	81 650	23.5	31.2	6
		22	6	39 500	......	82 000	22.5	28.5	6
		22	3	......	44 400	81 450	18.0	34.4	..
		22	7	......	40 700	82 050	22.5	31.8	..
		25	2	33 250	......	81 950	22.0	28.5	7
		25	6	40 000	......	82 200	24.0	34.7	7
		25	3	......	39 900	82 000	23.5	33.1	..
		25	7	......	40 050	82 150	22.5	33.8	..
D	8707-4	16	2	32 250	......	70 900	33.0	57.0	7
			6	27 750	......	70 200	34.5	56.2	7
			3	......	38 000	70 200	34.5	58.6	..
			7	......	71 200	71 200	32.5	56.0	..

Information as to the relative positions of the Johnson point and the drop-of-beam yield point are given in Table II. This shows for each pad the average value of the stress at the Johnson point and at the drop of beam, together with the number of bars covered by these averages, and the deviation of the maximum and minimum values from the average values.

It will be seen that in the tests furnished by Manufacturer F the value of the Johnson elastic limit is abnormally high in relation to the yield point, in some cases being actually higher than the yield point. The reason for this anomaly is not clear. It is possible that it can be explained by the fact that the bars for the stress-strain curves were loaded to 25,000 lb. per sq. in., then released and after the position of the strain gage was changed, the bars were reloaded and the test completed. The elastic limit may have been increased by the preliminary loading. Leaving these tests out of consideration, the value of the Johnson elastic limit averages 84.5 per cent of the yield point stress. The Running Tests showed that the average value of the elastic limit found by the method of Committee A-1 is approximately 89 per cent of the yield point stress, so that in round figures the Johnson limit is 95 per cent of the A-1 limit.

The table shows that in a set of tests for a given heat the values found for the Johnson limit show a greater deviation from the average value than is the case with the values found for the yield point. To put this in concrete form, average values for the deviations for the tests of each manufacturer have been computed and are as follows:

	AVERAGE DEVIATION OF MAXIMUM AND MINIMUM VALUES FROM THE AVERAGE VALUE.	
MANUFACTURER.	YIELD POINT BY DROP OF BEAM, LB. PER SQ. IN.	JOHNSON ELASTIC LIMIT, LB. PER SQ. IN.
A	625	1625
B	590	1560
C	596	333
D	935	2156
E	162	750
F	500	3364
G	800	1550

These figures show that if a number of bars are taken from a given pad of uniform steel the determination of the Johnson elastic limit gives more erratic results than the determination of the yield point by drop of beam.

The individual values of the representative curves reproduced in Figs. 6 and 7 are collected in Table III to permit comparison of the values of the Johnson limit and the yield point. For pad No. 25, heat No. E-1192, Manufacturer D, the two bars Nos. 2 and 6 show a difference of 6750 lb. per sq. in. with a difference in tensile strength of only 250 lb. per sq. in. The two bars Nos. 3 and 7 from the same pad show only 150 lb. per sq. in. difference between the yield point values with the same difference between the tensile strengths. Heat No. 7244, Manufacturer F, has four bars with a maximum difference of only 1000 lb. per sq. in. in the yield point values, while the other four bars show a variation of 8700 lb. per sq. in. in the Johnson values. Heat No. 8707-4, pad No. 16, Manufacturer D, on four bars tested shows a difference of 4500 lb. per sq. in. between the two Johnson values, 1450 lb. per sq. in. between the two yield points, and a variation of only 1000 lb. per sq. in. in the four tensile strengths.

Similar variations are found in the majority of the tests. It appears that the value of the Johnson elastic limit is determined by conditions which do not affect the usefulness of the casting in service.

The values of the yield point by drop of beam in different bars from the same casting vary in approximately the same degree as do the tensile strength, elongation and reduction of area, and therefore appear to stand in a closer relation to the service strength of the steel than is the case with the values found for the Johnson limit.

DISCUSSION.

Mr. Comstock.

MR. G. F. COMSTOCK (*presented in written form*).—It is evident that this paper is the outcome of a very large amount of work, and should certainly give authoritative information on the points that it really covers. The data on the yield points of steel castings are unquestionably complete and valuable, but apparently only a little work was done on the actual proportional or elastic limit. It is extremely unfortunate that an extensometer was not used in this work; the Berry strain gage is primarily an instrument for measuring strains in structures, and should not be relied upon for accurate extensometer research on test specimens because it measures strains along only one line on the surface of a specimen instead of the average strain in the specimen. It is noted in the paper that irregularities may have been due to bending of the specimen. With this uncertainty entering into practically all of these tests for "elastic limit," there seems little justification for the claim of precision in the work. The investigation seems to have been conducted by commercial laboratory methods rather than in the truly precise way demanded by scientific research, and the conclusion that all these specimens were plastic rather than elastic at low stresses does not necessarily follow from the results, which may appear irregular merely because of the instrument used or the manner of its use in these tests. The curves illustrating the paper have been drawn in such a way as to emphasize irregularities, whereas it would have been more in keeping with the method of testing to make them somewhat smoother and to ignore some of the lower points that are obviously inaccurate. Had this been done it seems likely that a proportional limit might have been found for most of the specimens, in spite of the use of the strain gage as a substitute for an appropriate extensometer. Certainly the production of permanent sets after light loading would have to be demonstrated before the theory of the lack of elasticity in this material at ordinary temperatures could be accepted.

Mr. Rogers.

MR. J. I. ROGERS.—I want to ask whether similar tests to these have ever been made on other steel materials, like forgings, rolled bars, etc. I think that if they had been made we would have the same results as shown on steel castings and that the variation of the elastic limit would be found especially in steel forgings and rolled bars in that there would be different conditions near the surface in forgings and bars than in their centers. Therefore, I would like to ask the question as to whether Mr. Fry believes that the variation of the elastic limit, which he has found in castings, is a condition peculiar to steel castings. **Mr. Rogers.**

MR. L. H. FRY.—I do not know of any exactly similar series, but I would like to point out that no reflection on steel castings is intended when it is said that the Committee A-1 method of determining the elastic limit is not well adapted for testing them. In the specifications of the Society, the A-1 elastic limit method is specified for quenched-and-tempered forgings and for cold-rolled axles, while the yield point by the drop of beam is specified for annealed forgings and for steel castings. There is no question of criticism of any material in saying that for that material the determination of the yield point gives a better method of testing than does the determination of the elastic limit. It is simply a matter of methods of testing. **Mr. Fry.**

MR. H. F. MOORE.—At the laboratories of the University of Illinois, where all sorts of tests come in, but not very many tests of any one kind, the opinion has been growing for some years that just such kinds of irregularities in the stress-strain diagrams as Mr. Fry found for steel castings are found, though to a much smaller degree, in tests of rolled steel specimens. The perfection of the straight-line relation between stress and strain is very largely a function of the delicacy of apparatus used. One admirable point made by Mr. Fry is that the cross-section paper used is a vital part of the apparatus for determining the elastic limit from a stress-strain diagram, and that the determination can be appreciably affected by the way in which the cross-section paper is used. **Mr. Moore.**

The speaker is in hearty agreement with the viewpoint that for some materials the yield point is the best criterion for elastic strength, for others the elastic limit determined as prescribed in certain of the Society's specifications for rolled steel (the "A-1 method"), for still other materials the elastic limit determined by the Johnson method, and for still other materials an elastic limit determined by still more sensitive methods. At the present time no one method will fit the needs of all metals.

It occurred to the speaker that the irregularities which Mr. Fry noted, and which he ascribed to plastic action in the steel casting material, might be explained either on the ground of plastic action or on the ground of non-homogeneity of structure (due to minute blow holes or inclusions), with consequent yielding at areas of localized high stress.

Mr. Lynch.

MR. T. D. LYNCH.—I would like to make a few remarks in connection with Mr. Fry's paper, which is certainly one of very great interest to all of us. The irregularity of the elastic limit of the tests shown in the stress-strain tables does not conform to the many tests which we have made on similar material in our laboratory and I am wondering if it is not due to the irregularities inherent in the samples themselves. Internal stresses are often present in test pieces due to non-uniformity of thermal treatment or to the effect of machining the test piece from the coupon. This latter operation may easily set up stresses of more or less magnitude and the greater the tearing effect of the tool, the greater the stresses. We have obtained more uniform results when the test piece was permitted to rest for some time after it had been finally machined to size, and test curves made from such aged samples have been found to be very much more consistent.

Some years ago I had occasion to study the effects of normalizing gears for use in railway service and in order to have a fair representation of the rim of the gear it was decided to procure a series of 59 samples made from as many different heats of steel. Each sample was 6 by 6 by 1½ in., cast separately, and with independent risers to insure sound castings. The chemical analyses and physical tests on each of the unannealed samples were consistent and reasonably close together. After testing in the unannealed condition, ten of these samples were normalized by heating in a furnace to 875° C. and then removing from the furnace and allowing to cool freely in the air, after which additional test specimens were prepared. The remaining portion of the samples were then heat treated by heating to 875° C. and quenching in oil, followed by drawing at 600° C. for 30 minutes. The average results from the ten samples were as follows:

CHEMICAL ANALYSES.

	CARBON, PER CENT.	MANGANESE, PER CENT.	PHOSPHORUS, PER CENT.	SULFUR, PER CENT.	SILICON, PER CENT.
Heat test	0.265	0.66	0.051	0.038	0.285
Check test	0.285	0.655	0.050	0.035	0.29

PHYSICAL TESTS.

	ELASTIC LIMIT, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	TENSILE STRENGTH, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT.	REDUCTION OF AREA, PER CENT.	BRINELL HARDNESS.
As cast	22 600	38 400	71 690	13.2	15.6	140
Normalized	43 800	45 980	77 730	21.9	34.2	159
Heat treated	51 250	51 790	83 830	26.	43.5	165

Mr. Lynch.

Each item under "Physical Tests" was very much improved by normalizing and they were further improved by heat treatment. The samples when normalized were 5 by 6 by $1\frac{1}{2}$ in. and when heat treated they had been reduced to 4 by 6 by $1\frac{1}{2}$ in. The specimens in each case were cut out by a shaper to $\frac{3}{4}$ by $1\frac{1}{2}$ by 6 in., turned to standard $\frac{1}{2}$-in. diameter by 2-in. gage length, aged for 24 hours or its equivalent and placed in boiling water for 10 minutes before testing.

A study of the physical test table shows an improvement in thermal treatment of steel castings that is worthy of consideration. The following table is prepared to show the improvement in the series of tests made by taking the "as cast" material as our base.

PER CENT IMPROVEMENT BY THERMAL TREATMENT.

	ELASTIC LIMIT, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	TENSILE STRENGTH, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT.	REDUCTION OF AREA, PER CENT.	BRINELL HARDNESS.
As cast	0	0	0	0	0	0
Normalized	93.8	19.7	8.4	65.9	119.2	13.6
Heat treated	126.5	34.8	16.9	96.9	178.8	17.8

Mr. Force.

MR. H. J. FORCE.—During the past 15 years we have made a good many thousand tests of steel castings, and those tests have been made by taking the yield point by the drop of the beam. These castings have been put in service, and I cannot recall a single failure of the castings due to a low elastic limit, unless there was a flaw of some kind in the casting. It does seem to me that the method of testing—I am now talking about cast steel only—by the drop of the beam, is one that is entirely satisfactory to at least some of the railway companies who are buying steel castings in large quantities.

Mr. Fry.

MR. FRY.—I was rather surprised at Mr. Comstock's objection to the Berry strain gage. If we are to write the Berry strain gage off our books, we have got to scrap a lot of work that has been done for the Society. Also, I would like to point out that the use of a more accurate extensometer might have accentuated some of the irregularities shown, but it certainly would not have changed the main characteristics of the curves on which the conclusions are based.

Mr. Moore spoke about the use of the term "plastic." In thinking that the cast steel was plastic, I was not paying so much attention to the irregularities of the curve as to the fact that the curve showed an increasing curve downward. If Prof. Moore will permit a steelworks man to attempt the language of the college, I would say that the radius of curvature was constantly decreasing.

Mr. Lynch spoke of the irregularities being probably irregularities

Mr. Fry. in the samples. This is undoubtedly true. The curves shown in Figs. 6 and 7(*a*) of the paper are from the same heat of the steel. Of these four curves from the same heat of steel, two show a straight line law, and two irregular curves. Part of the thought back of this work was to illustrate just what irregularities might be expected in coupons from the same casting treated in the normal way in which steel castings are treated in the course of manufacture.

ELECTRICAL AND MAGNETIC WELD TESTING AS APPLIED TO BUTT-WELDED STEEL PLATES.

By T. Spooner[1] and I. F. Kinnard.[2]

Introduction.

In spite of the very rapid progress made in recent years in the application of arc and gas welding, this progress would have been more rapid if at the same time there had been developed a reliable and simple method of determining the quality of welded joints. Provided plenty of reliable and competent operators are available, it is well known that many important structures such as large tanks, steel ships, boilers and perhaps the steel frameworks of bridges and buildings could be safely joined together by welding alone. However, since the results are always in doubt where the human element enters in and since visual inspection alone will not reveal the presence of slag inclusions, incomplete fusion of metal, etc., the applications of welding methods have been greatly retarded for important structures where reliability is essential.

There are various possible methods of inspection available such as X-ray analysis, acoustical methods, electrical tests, magnetic tests, etc. This paper will describe some preliminary laboratory tests to determine the possibility of applying electrical and magnetic methods for testing the quality of butt welds joining steel plates. It should be understood that the purpose of these preliminary tests was merely to determine whether or not such methods showed promise of ultimate success and not to develop commercial testing apparatus.

Samples.

Four pairs of steel plates having the following dimensions were butt-welded by an experienced operator:

Plate.	Thickness, in.	Length of Weld, in.
A	½	16
B	¼	24
C	½	24
D	½	24

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[1] Research Engineer, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

[2] Research Engineer, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

The joints were made according to a predetermined schedule and were designated by the welder as good, fair and poor, over various sections as will be noted later.

METHODS OF TEST.

The method of application was similar for the electrical and magnetic methods of test and consisted in measuring the electrical or magnetic potential drop across the weld with a definite e.m.f. or magnetic potential applied on opposite sides of the weld. This drop was compared with the drop over an equal length of unwelded plate. The e.m.f. or magnetic potential was applied at points fairly close to the weld in order to localize the effect. If the e.m.f., for instance, had been applied at the edges of the plate parallel to the weld, the current would have distributed itself inversely as the resistivity and the potential drop across the various portions of the weld would have been nearly the same regardless of the quality.

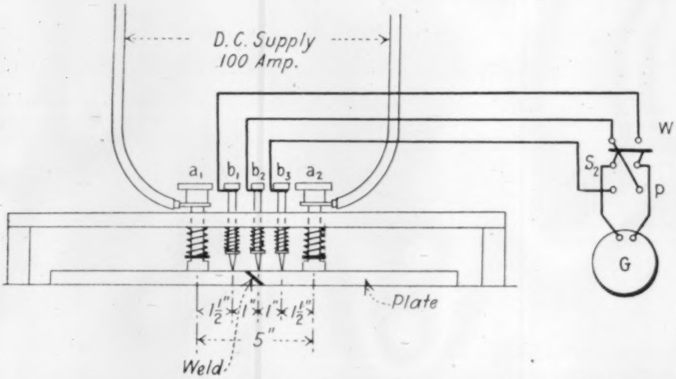

FIG. 1.—Diagram of Apparatus for Electrical Tests of Butt-Welded Joints.

Electrical Tests.—The apparatus constructed to make use of the electric current for weld testing is shown diagrammatically in Fig. 1. The current, in this case 100 amperes D.C., was passed into the plate through two heavy brass posts a_1 and a_2. A galvanometer was connected through the switch S_2 to either b_1-b_2 which was across the weld, or to b_2-b_3 which was across an equal distance on the plate. Consequently, readings could be readily obtained for any point in the weld which indicated the difference, if any, between the weld and plate at that point. In general the weld had a higher resistance than the plate and consequently the potential drop was greater for the former. The difference between the above readings expressed as a percentage of the plate readings represents the percentage decrease in the quality of the weld based on the plate. The quality of the weld is expressed as 100 minus the percentage decrease as just defined.

The scale was first removed from the plate over the portion to be tested. The plate was then marked off into 1-in. strips and readings were taken at the center of each strip. In all cases these readings were repeated several times and it was found that reasonable checks could be obtained.

Magnetic Tests.—A magnetic tester was designed incorporating the same general principles utilized in the electrical method. Fig. 2 shows the general arrangement. A method of measuring magnetic potential drop was originally described by Chattock[1] in England and was later used by Rogowski[2] in Germany. A modification of the general principle, due to Fahy[3] and incorporated in his Simplex permeameter, was used in our tests. Fig. 2 shows the general arrangement of the apparatus and connections, and Fig. 3 is a reproduction of the tester itself. In this case the soft iron posts c_1, c_2 and c_3 were used as potential contacts and the drop in magnetic potential across the weld and plate respectively was obtained ballistically by means of the air coils s_1 and s_2 which were connected to a ballistic galvanometer. The set-up was arranged so that when switch S_1 was in position D the coils were connected differentially, and when in position P the coil across the plate only was connected to the galvanometer. Only sufficient

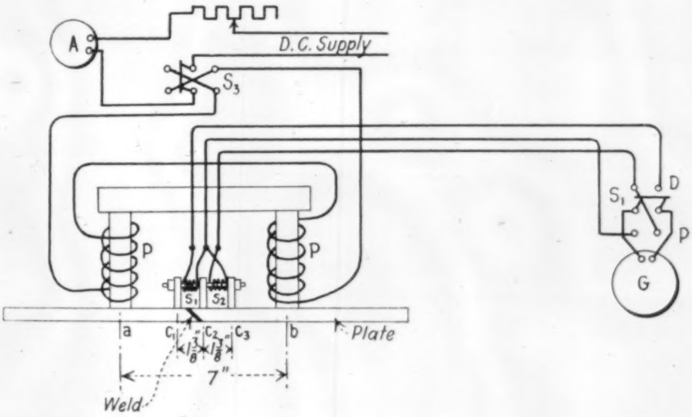

FIG. 2.—Diagram of Apparatus for Magnetic Tests of Butt-Welded Joints.

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[1] *Phil. Mag.*, Vol. 24, p. 94 (1887).

[2] *Archiv. für Elektrotechnic*, Vol. 1, p. 141 (1913).

[3] *Chemical and Metallurgical Engineering*, Vol. XIX, Sept. 1 and 15 (1918).

exciting current was used to induce a flux in the plate at about the value of maximum permeability, as it was found for instance that 0.5 ampere worked better than 2 amperes.

After experimenting it was found that for the most consistent results it was necessary to raise the potential contacts from the plate a slight distance with some non-magnetic material. This was done to equalize the effects of scale and non-uniform contacts. Due to the fact that, in some cases, the plates were badly bent and twisted, better results were also obtained by rounding the main contacts at *a* and *b*. It is necessary for proper functioning that the potential posts c_1, c_2 and c_3 be symmetrically spaced in respect to each other and to the magnet cores *a* and *b*.

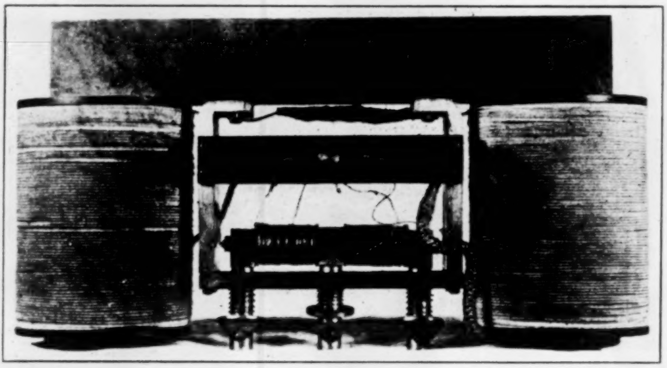


FIG. 3.—Apparatus for Magnetic Tests of Butt-Welded Joints.

In the magnetic test, readings were taken along the plate at 1-in. intervals as in the electrical tests. The quality of the weld is expressed as in the electrical tests.

Tension Tests.—After completing the electrical and magnetic tests, the plates were cut into 1-in. strips at right angles to the weld and the tensile strength of the strips determined. The cross-section was taken equal to that of the normal plate outside the weld. In most cases rupture occurred within the weld, but in a few instances the strip broke outside, showing that the weld was stronger than the plate. In all cases an average value was obtained for the strength of material in the plate so that the strength of the weld could be expressed as a percentage of that of the plate.

TEST RESULTS.

The electrical and magnetic test results for the various plates, together with the quality as reported by the welder, are shown in Figs. 4 to 7. The electrical and magnetic testing apparatus was located midway between each pair of vertical dotted lines as indicated by the test points. For the tensile tests the plates were supposed to have been cut along the dotted lines. The machining was not accurately done, however, as indicated by the cross-hatched portions at the top of the figures which show the actual cutting positions. The results shown for the electrical and magnetic tests represent data obtained after a good many trials and check runs which were in some cases made on both sides of the plate. A weld equal in quality to the plate is represented as 100 per cent. For points below the 100-per-cent line, the weld is poorer than the plate and above, better.

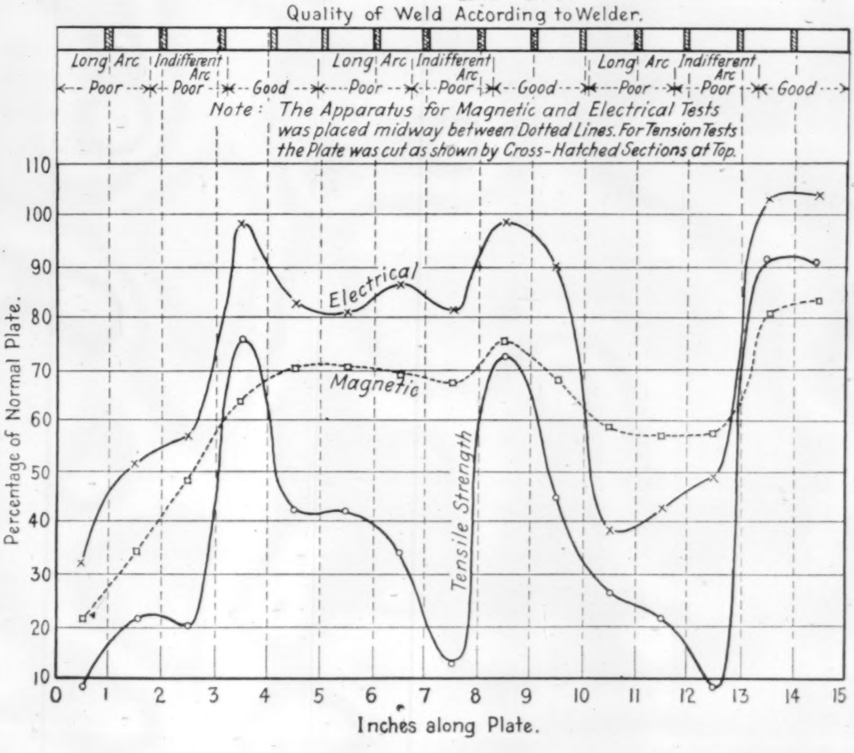
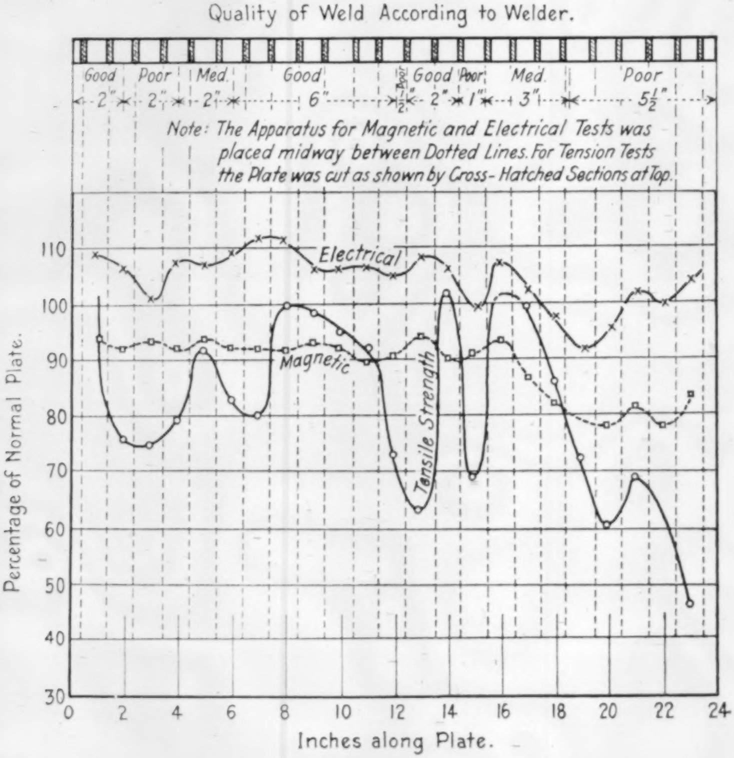


FIG. 4.—Results of Electrical, Magnetic and Tension Tests, Plate A.

DISCUSSION OF RESULTS.

Before considering the results on each plate in detail the following points may be noted. In comparing the electrical and magnetic tests with tensile strength we must make allowance for the fact that the latter tests were made on isolated strips and represent absolute values, while in the former tests adjacent strips have an influence on the value read. Although this does not prevent the electrical or magnetic testing from showing up isolated bad spots, it may modify them or slightly displace their apparent position since the measurements could not be completely localized. If a good and bad spot are adjacent, the electrical and magnetic tests will give a more or less mean value, whereas the tension test, which is the absolute test value for one inch, is not of course influenced by the adjacent material since this material has been removed. Moreover, the tension tests tend to be too low as compared with the quality of the completed weld for two reasons:



Note: The Apparatus for Magnetic and Electrical Tests was placed midway between Dotted Lines. For Tension Tests the Plate was cut as shown by Cross-Hatched Sections at Top.

FIG. 5.—Results of Electrical, Magnetic and Tension Tests, Plate B.

First, in many cases the two plates welded were no longer in the same plane due to shrinkage caused by unequal cooling and therefore tension tests produced bending strains as well as normal strains; and

Second, if a small slag inclusion or other weak spot was present near the edge of a strip it would tend to spread on pulling, thus reducing the strength of the strips below that to be expected of the completed weld.

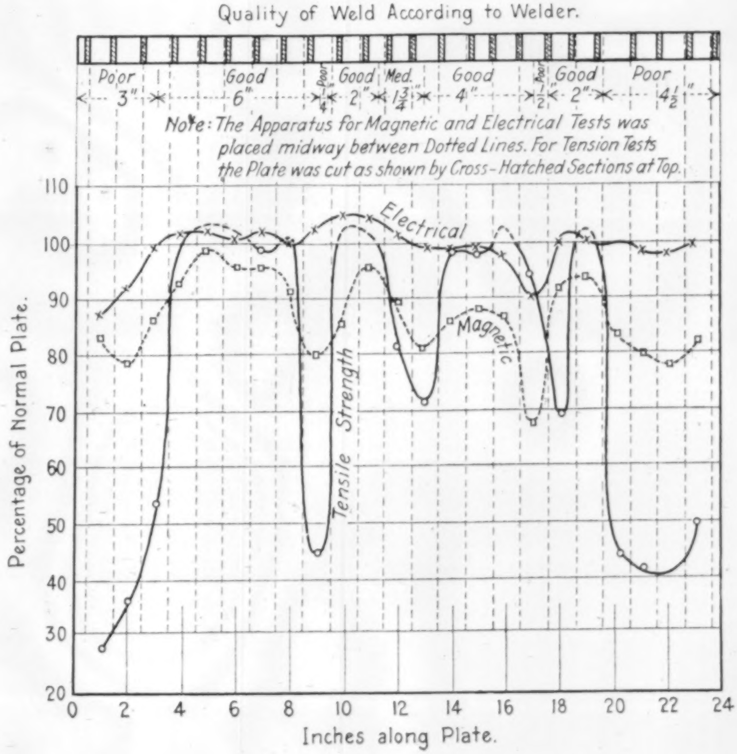


FIG. 6.—Results of Electrical, Magnetic and Tension Tests, Plate C.

It is probable, then, that the tension tests represent a worse condition than actually existed. Moreover, it is quite possible that the electrical and magnetic results more nearly represent the true quality of the weld as a whole, although they probably indicate a weld quality somewhat superior to the actual quality.

Plate A.—This plate was tested a large number of times by both methods. As shown by the curves (Fig. 4) the electrical test follows the tensile strength more closely than the magnetic test does. The latter, though, indicates that the weld is very bad in almost every part. The bad region between the 5 and 8-in. points is somewhat slighted by both tests, although it is not shown as "good" by either one. The good spot between the 3 and 4-in. points is shown by the electrical test but not by the magnetic. It is probable that an isolated good spot will not be picked out by the magnetic test, but the results seem to show that isolated bad spots are readily located, which is presumably more important. It will be well to call attention to the fact that in testing this plate the magnetic tester had not been developed to the working efficiency that was reached later. Therefore, there is a possibility that the poor 5 to 8-in. section would have been better detected had it been tested under the later conditions of test. This plate had the poorest welding of the four, which is shown by all the tests.

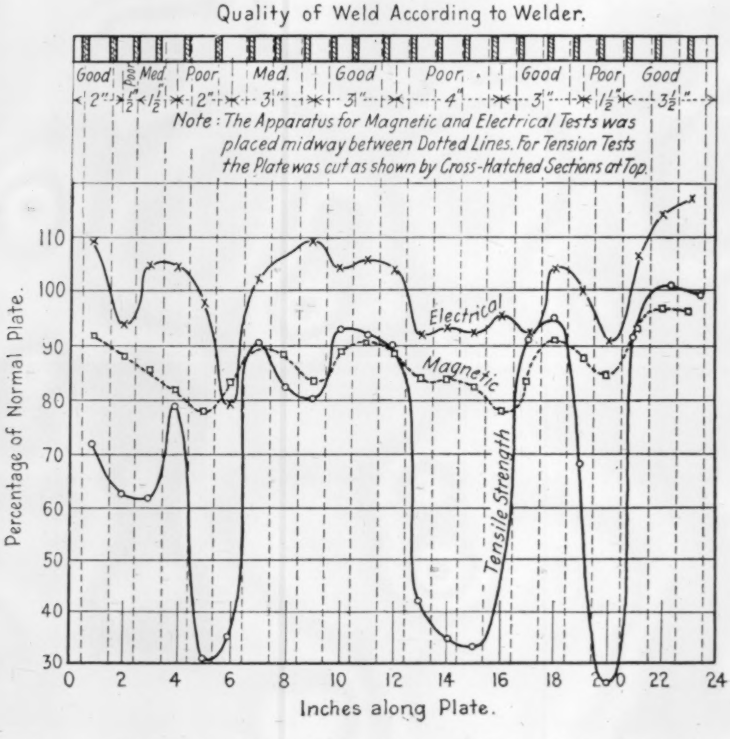


FIG. 7.—Results of Electrical, Magnetic and Tension Tests, Plate D.

Plate B.—According to the magnetic test on this plate it would be pronounced a good weld with the exception of the end 18 to 24 in. There are evidently some isolated bad spots at some other points, but these are not sufficiently bad to have much effect on the magnetic data. The electrical test in general shows much the same results as the magnetic. In general we would say that this was the best plate of the four, but that the detail of variations was not brought out very well by either of the two tests.

Plate C.—The magnetic test on plate C seems to follow the tensile strength remarkably well, although the magnitude of the percentages are somewhat different, as would be expected. The strip at 17 in. shows a bad spot magnetically while in the tension test this bad spot seemed to be located at 18 in. However, according to the data on the original welding there was a bad spot located at 17 in. and it is probable that it extended into the 18-in. region. On account of the adjacent good weld at 19 in. the effect of the bad spot was more prominent at 17 than at 18 in. The electrical test on this plate was not so successful and shows a uniformly good plate with the exception of the strip at 17 in. and the section from 1 to 3 in.

Plate D.—Again in this plate the magnetic test follows the shape of the tensile strength curve quite closely. The electrical test also shows quite good results although the latter is displaced above the 100-per-cent line too much. The bad spots in the plate are quite definitely picked out by both tests.

CONCLUSIONS.

1. It would seem that the foregoing tests will pick out faults in welds irrespective of what type they may be. For instance, it was brought out by an examination of the test strips that a small cross-section at the weld shows up magnetically. On the other hand if there is a surplus of metal at the weld and part of it poor, this condition is detected.
2. From the experimental work here reported it seems that the magnetic methods give the more consistent results.
3. For butt-welding it is quite feasible to definitely state from the magnetic test whether a weld is good, fair or poor when the results are properly interpreted.
4. While the electrical or magnetic tests do not detect small isolated bad spots with certainty, a fairly poor weld extending over considerable distance will be indicated without the slightest possibility of doubt.

5. It is apparent that the tension tests indicate much poorer quality of welds than the magnetic or electrical. However, from considerations mentioned above we believe that the tension tests indicate a poorer quality than actually exists while the electrical and magnetic tests show more nearly the average quality.

6. All of the welds with the exception of plate A, Fig. 4, would be considered good average welds. For this plate, the tension, magnetic and electrical tests all agree that this is a poor weld.

7. It should be possible to readily devise a simple and portable apparatus for applying these methods, especially the magnetic, for commercial weld testing. The magnetic method should be more readily applicable since actual metallic contact between the testing apparatus and the plate is not essential.

8. These results open up a line of approach to weld testing in general. It remains to be seen whether the foregoing methods can be successfully applied to lap-welded joints and other untried forms. The application to butt welding alone should be quite important to any industry that utilizes this type of weld extensively.

MERCHANT BAR IRON MADE BY THE BUSHELED SCRAP PROCESS.

By W. M. Myers.[1]

Merchant bar iron is wrought iron made from reworked iron scrap or a reworked mixture of iron and steel scrap, as described in the Tentative Specifications for Merchant Bar Iron (Serial Designation: A 85 - 21 T) of this Society. While there is still some difference of opinion, the most generally accepted distinction between steel and wrought iron is that steel is produced from an ingot, bloom, or billet cast from material in a molten state, while wrought iron is produced from material that has been brought to a welding heat or plastic stage. The so-called wrought iron, as commercially understood, may be divided into two groups: wrought iron made by the older process in the puddling furnace, in which cast iron is converted to wrought iron, and wrought iron made by the busheling process.

The busheling process is well described in the standard definitions of this Society, as "The process of heating to a welding heat in a reverberatory furnace, miscellaneous iron, steel or a mixture of iron and steel scrap cut into small pieces." This process came into use, commercially, about the time of or a little later than the introduction of the Bessemer process of making steel. When steel commenced to replace wrought iron made by the puddling process, on account of the high cost of producing wrought iron, a number of mills, especially in the middle west, that had previously been puddling mills, were gradually changed over into busheling mills. The present production of busheled bars, while small compared to steel bars, is nevertheless of considerable proportions and has outstripped, from a point of tonnage, the production of puddled wrought-iron bars. Exact statistics are not at hand as to the actual production of busheled bars, as the figures compiled by the American Iron and Steel Institute consolidate the output of puddled iron bars and busheled bars and other products of wrought iron. In the year 1920 there were produced 1,377,000 tons of finished rolled forms in iron; of this amount 252,000 tons were skelp iron and 663,000 tons were merchant bars, the balance being made up of bolt and nut rods, horseshoe bars, spikes and chain rods and some other minor forms. The skelp iron is practically all produced from puddled pig iron, and of the approximately one million tons of merchant bars and the other grades, such as horseshoe bars, etc., it is safe to say that at least two-thirds of the tonnage was produced by the busheling process.

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[1] General Manager, The Highland Iron and Steel Co.

The busheling process consists, as described above, in heating small pieces of iron or steel scrap on the hearth of a reverberatory furnace. There are two distinct types of busheling furnaces, the "sand bottom" and the "cinder bottom" furnaces. The bottom of the former is made up of fire sand and is similar in this respect to a heating furnace. The furnace is arranged so that the cinder produced is drained frequently, leaving a comparatively dry working bed. The cinder bottom furnace, on the other hand, is similar to a puddling furnace, the bottom consisting of a cast-iron plate protected with cinder. The furnace is tapped less frequently, and the bottom of the furnace contains a considerable quantity of molten cinder. Allied to these two types is the so-called "Pile on Board" furnace, in which pieces of scrap are piled, ordinarily, on a board about 12 or 15 in. square in a pile weighing from 150 to 300 lb., depending on the mechanical means for handling it.

The above are all so-called hand furnaces. In recent years mechanical busheling furnaces have been designed and will be described later.

In the sand bottom furnace, usually one ball is made at a time, weighing anywhere from 150 to 400 lb. The pieces of scrap, called busheling scrap, are charged into the furnace by hand or with a scoop, together with about 25 per cent of wrought-iron or soft steel turnings or drillings. This material is spread on the hearth of the furnace by the operator with a rabble to insure uniform heating, and is brought to a welding heat. It is then formed by the operator into a ball, which is taken from the furnace to a squeezer or in some cases to a hammer.

In the cinder bottom furnace, the process is similar where busheling scrap alone is used. These furnaces are frequently double furnaces and are worked from both sides, so that as many as four balls may be made at one charge. In the cinder bottom furnace, cast iron is sometimes added, in the shape of borings or drillings. The proportion of cast iron varies, but is usually about one-third of the charge, and the process then becomes a semi-puddling process in that the cast iron must be converted into wrought iron. However, on account of the small percentage of cast iron in the mixture and the finely divided form in which it is used, the conversion takes place more rapidly and with less labor than in the regular puddling process.

After the balls are taken from the furnace, the process is the same as in making wrought iron from puddled pig iron, that is, the balls go through a squeezer and then through rolls and are made into a semi-finished product, known as scrap bar or busheled bar, which is similar to the muck bar made from puddled pig iron. The material is finished in the same manner as refined wrought iron, either by piling the scrap bar in solid piles or making it into fagots, or box piles.

Within the last few years, several mechanical busheling furnaces have been designed, the two in successful operation being the "Ely Furnace" at Terre Haute, Ind., and at Lebanon, Pa., and the "Sellers Furnace" at Mayfair, Ill. In these furnaces, the scrap is first heated as in the hand furnaces and formed into a ball by revolving the furnace, and the rabbling and all hand manipulation by the operator is eliminated. The mechanical furnace eliminates the laborious work and correspondingly high wage paid the hand busheler, and the balls may be made into units of approximately twice the weight of those in the hand furnace, which improves the quality accordingly.

TABLE I.—RESULTS OF PHYSICAL TESTS ON BUSHELED MERCHANT BAR IRON.

	Test Piece Dimensions.[1]	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 8 in., per cent.	Reduction of Area, per cent.
Mill A	0.749	35 400	51 200	26	45.9
	0.750	35 300	50 700	29	46.3
	0.742	36 500	52 000	29	47.00
Mill B	0.755	38 000	47 600	31	58.8
	0.756	37 600	47 400	32	56.3
	0.756	37 700	47 600	31	59.6
Mill C	0.790	37 900	49 800	31	50.0
	0.788	37 900	50 000	28	51.2
	0.781	38 200	51 500	30	49.4
Mill D	0.785	42 500	51 400	29	54.5
	0.780	39 500	51 700	30	48.3
	0.787	36 700	50 600	30	53.7
Mill E	0.750	32 500	47 100	29.5	53.5
	0.755	33 700	47 700	28.0	48.8

[1] All bars were of $\frac{3}{4}$-in. stock and were tested as rolled.

The finished merchant bar has all the appearances and characteristics of other wrought iron. As distinguished from steel, it is of a fibrous nature instead of crystallin, and carries the layers of included slag or cinder between the fibers of iron. The quality naturally depends on the materials used and the care and skill in the manufacturing processes. The busheling scrap should be of low-carbon steel or wrought iron, and extremely heavy pieces should be avoided, as well as light sheet iron or similar material. While some specifications prohibit the use of any turnings or drillings, it is generally considered that if these are of good quality—that is, free from high carbon or alloy steels, which prevent proper welding—turnings and drillings are of benefit rather than otherwise, as they fill the interstices between the pieces of scrap and seal the ball into a more solid mass.

The physical properties of the busheled bar are practically the same as those of other wrought iron; in fact, this Society's specifications call for the same physical properties as those specified for refined wrought-iron bars made by the puddling process. In service, also, the busheled bars give the same results as other wrought iron. On account of the slag or cinder inclusion, if that theory is tenable for other wrought iron, corrosion is resisted, and the fibrous nature of the material gives it the same shock resisting properties.

The results of some tests made by Committee A-2 on Wrought Iron of this Society, on busheled bars furnished by a number of different mills, during their investigation into the kind of busheled scrap bars which were then on the market, are given in Tables I and II. Many other tests could be cited, but those given are representative.

Attention is called to the chemical analyses reported in Table II. In the case of wrought iron, any close chemical specification is not considered of vital importance. It is difficult to get a representative sample for analysis, and the quality of the bar is more dependent on the workmanship and proper heating than on any minor difference in the analysis, although, of course, it is important that scrap high in carbon, or other elements which prevent proper welding, shall not be used. There is in a measure, however, an automatic rejection of such high-carbon material, as it will not weld with the other scrap and is either not picked up in the balling, or shows up in either the semi-finished or the finished bar.

TABLE II.—CHEMICAL ANALYSES OF BUSHELED MERCHANT BAR IRON

		Carbon, per cent.	Manganese, per cent.	Phosphorus, per cent.	Sulfur, per cent.	Silicon, per cent.
Mill A	Sample No. 1	0.020	0.240	0.053	0.036	0.253
	Sample No. 2	0.020	0.258	0.062	0.036	0.182
Mill B	Sample No. 1	0.020	0.369	0.019	0.032	0.178
	Sample No. 2	0.078	0.341	0.035	0.030	0.242
Mill C	Sample No. 1	0.049	0.101	0.064	0.022	0.141
	Sample No. 2	0.052	0.110	0.068	0.024	0.070
Mill D	Sample No. 1	0.081	0.388	0.024	0.043	0.038
	Sample No. 2	0.095	0.572	0.016	0.040	0.038
Mill E	Sample No. 1	0.049	0.397	0.026	0.032	0.204
	Sample No. 2	0.106	0.354	0.023	0.055	0.315

As to the commercial needs for this material, it stands in a measure between the refined puddled wrought iron and mild steel, and is useful for many purposes. It results in the economical use of a large tonnage of scrap iron and steel which otherwise would have to go through the open-hearth furnace, and the scrap which is least desirable for the open-hearth furnace is most desirable for the busheling furnace, that is, the wrought iron and extremely low-carbon steels.

DISCUSSION.

Mr. Aston.

MR. JAMES ASTON (*by letter*).—No comments are necessary upon the salient features of Mr. Myers' paper. The use of scrap by busheling is a commendable economic procedure; the importance of this industry answers the question of the specific utility of the product. My remarks are intended as a general caution to the use of wrought iron, and not in criticism of the facts of the paper.

Even though it could be admitted that a busheled product may be made of high grade, extreme caution is necessary because of the acknowledged difficulty of securing the proper quality of scrap in the open market; a normal difficulty which is much aggravated for large outputs or in times of industrial activity. The problem is vitally different from scrap using in the steel industry, where the identity of the raw materials are merged or lost in the melting and refining operation.

Any consideration of wrought iron must bear in mind the composite nature of the product—base metal and slag. It is of right quality only when both ingredients of the composite are right, and when their degree of incorporation or admixture is right. The puddling operation disintegrates the base metal to a degree and regularity impracticable with ordinary selection of scrap. Furthermore, the slag will depart from normal wrought-iron characteristics if we depend upon oxidation of the iron alone, and lose the benefit of silica and phosphate resulting from normal refining of pig iron in puddling. In addition there is the uncertainty and irregularity of base metal in a busheling operation.

That a fibrous characteristic is obtained in busheled bar is not proof positive of the true nature of the product; but only signifies how relatively easy it is to break the normal crystallin fracture of the base metal by the incorporation of mechanically included slag or oxides. The true criterion of equality is disclosed only by the microscopic, which brings out the nature of the metal and slag in their true relation.

Physical tests of wrought iron do not mean much unless accompanied by a knowledge of the practice by which the material was made. Better to have no physical test and a sound knowledge of the mill practice, than to depend upon tests alone and dismiss the history of manufacture from consideration. Tensile tests are advisable to control the product of the manufacturer, but are of no value to fix the identity

Mr. Aston. or quality of an unknown product. If steel will easily pass the specifications for wrought iron, why should not a busheled mass of this material do the same, and where is the link tying such passing with wrought iron quality?

It is equally true that chemical analysis does not serve to identify the quality of wrought iron. For example, a steel devoid of slag could be made identical with the best puddled iron in analysis; but the silicon and phosphorus would be directly alloyed with the base metal, and the analysis would lose its value in interpretation because it failed to place the elements in their true distributions in metal or slag. On the contrary, high carbon and manganese, the latter in particular when above 0.10 per cent, are quite indicative of a busheled product. This is not because of any necessarily harmful influence of these elements, but because in normal puddling practice they are removed during refining, and it is not possible or practicable to make additions as is the case with a heat of steel.

However, it is not true that chemical analysis of wrought iron is not capable of reasonably close control or is without significance. The general characteristics are dependent upon raw materials and methods; naturally these may vary according to necessity or the standards set by the experience of the manufacturer. Control of raw materials and practice, with proper work in intermediate stages, will give a finished product of an analysis conforming to reasonably close specifications. What we need is an analytical method which will differentiate the slag from the metal, and enable the proportions of each in the composite, and the separate analyses of each, to be made as a matter of works routine. We are striving for such a result as a vital factor in control and development of wrought iron of quality.

SOME OBSERVATIONS ON THE "NICK-BEND" TEST FOR WROUGHT IRON.

By Henry S. Rawdon[1] and Samuel Epstein.[2]

Introduction.

In practically all specifications concerning wrought iron in the form of rods and bars and, very often, plates, the material is required to pass satisfactorily a "nick-bend" test. The clause from the Standard Specifications of this Society for Staybolt, Engine Bolts and Extra Refined Wrought-Iron Bars (Serial Designation: A 84 - 21)[3] may be quoted as typical of this requirement:

> "The test specimen when nicked 25 per cent around with a tool having a 60-deg. cutting edge, to a depth of not less than 8 nor more than 16 per cent of the diameter of the specimen, and broken, shall show a wholly fibrous fracture. Bend tests may be made by pressure or by blows."

In some grades of wrought iron, a certain percentage of crystallin area is permitted in the fracture of a test specimen broken as described above. For example, the Standard Specifications of this Society for Wrought Iron Plates (Serial Designation: A 42 - 18) permit 10 per cent crystallin area in a fractured nick-bend specimen of wrought-iron plate. According to the Navy Specifications (47 I 1a), a few crystallin spots will be tolerated in the fracture of a nick-bend specimen of wrought-iron bars for the manufacture of chain, provided they do not exceed 10 per cent of the total area of the face of the fractured specimen.

The requirements of British specifications for wrought iron may be illustrated by the following clause from Specification 51 of the British Engineering Standards Association:

> "Test pieces . . . shall be lightly and evenly nicked on one side with a sharp cutting tool and bent back at this point through an angle of 180 deg. by pressure in a press or by a succession of light blows, when they shall show a fibrous fracture free from slag or dirt. The same test pieces when nicked all around and broken off short shall show a fine uniform crystallin fracture."

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[1] Physicist (Metallography), U. S. Bureau of Standards.

[2] Assistant Physicist (Metallography), U. S. Bureau of Standards.

[3] 1921 Book of A.S.T.M. Standards, p. 317.

The following clause[1] may be taken as representative of the French method of carrying out this test:

> "The bars, notched by machine or by a chisel, are broken suddenly by a hand sledge or by a power hammer while firmly held at one end. The iron ought never to show in its texture large brilliant or laminated crystallin areas; the grain should be semi-fine with slight tears; the fiber should be white, elongated and without traces of slag."

It is quite evident from the preceding that the "nick-bend" test for wrought iron is a common requirement, also that there are pronounced differences to be noted in the manner in which this test may be carried out. In none of the specifications for wrought iron examined by the authors was there any definite suggestion offered as to the real significance of the crystallin areas in the fractures of the "nick-bend" specimens. It is generally admitted by testing engineers that considerable experience is necessary in conducting this test and in interpreting the results. Numerous requests for information concerning this test received by the U. S. Bureau of Standards indicated clearly the need for definite information along this line and it was primarily for the purpose of obtaining data for use in replying to such inquiries that a study of the "nick-bend" test was undertaken.

The results are offered to this Society for consideration principally for their suggestiveness rather than as a comprehensive discussion of this method of testing. If the most obvious shortcomings of the test are realized and the real nature of some of the results obtained made clear, as well as the need for a stricter definition of the test, the purpose of the authors will have been accomplished.

SCOPE OF INVESTIGATION.

In brief, the investigation consisted of the fracturing, under known conditions, of nicked bars of a number of grades of wrought iron, the composition, mechanical properties and structure of which had been carefully determined. The material, which was contributed by various manufacturers for the purpose, in most cases had been manufactured to meet certain A.S.T.M. specifications. Nicked bars, representative of the different materials furnished, were broken under different conditions varying from a simple transverse bending of a specimen supported at the ends to a severe single-blow impact test (drop test). The appearance and nature of the fracture produced under these different methods of fracturing was, of course, the feature which received most attention.

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[1] Spécifications techniques set cahiers des charges unifiés; Chemins de fer Français. Ch. Beranger, publisher, Paris.

MATERIALS USED.

The general nature and character of the different irons used in the investigation are summarized in Table I, the manufacturers who supplied the material being referred to by letters. The order in which the materials have been arranged has no significance other than that it represents the sequence in which they were received at the Bureau of Standards from the manufacturers. Material "E" represents an intermediate stage in the manufacture of wrought iron and should not be considered as representative of the finished product of any manufacturer. It was included in the series for the purpose of showing in some measure the extent to which the properties of the finished product are influenced by the amount of "refining" received by the material.

Most of the irons were in the form of 1-in. diameter rods of 12-ft. lengths. These were cut up into specimens 6 in. in length, each one being marked so as to record its location in the bar. In the following tests, duplicate specimens were used for the most part, care always being taken that for such duplicates, two specimens adjacent to each other along the length of the bar were chosen so as to eliminate possible variations in properties along the length of the bar.

TABLE I.—MATERIALS USED.

Manufacturer.	Designation of Material.	Nature of Material.
A	A 1	1-in. diameter engine bolt iron, Grade A, A.S.T.M. Specifications A 84 - 21.
	A 2	1-in. diameter engine bolt iron, Grade C, A.S.T.M. Specifications A 84 - 21.
	A 3	1-in. diameter all-puddle bar A.S.T.M. Specifications A 41 - 18.
B	B 1	1-in. diameter staybolt iron, Grade A, A.S.T.M. Specifications A 84 - 21.
	B 2	1-in. diameter extra refined, Grade C, A.S.T.M. Specifications A 84 - 21.
	B 3	1-in. diameter refined iron, A.S.T.M. Specifications A 41 - 18.
C	C	1-in. diameter special grade, double refined iron.
D	D	1-in. diameter staybolt iron, Grade A, A.S.T.M. Specifications A 84 - 21.
E	E	⅝-in. bar, from first rough rolling of puddled bloom, squeezed from puddled ball (intermediate product).

Chemical Composition.—It is quite generally recognized that, for a material which lacks homogeneity to the extent that wrought iron does, the chemical composition is usually of slight significance. However, for purposes of reference and comparison, there are given in Table II the results of the chemical analyses of the materials used.

Mechanical Properties.—In Table III are summarized the results of the mechanical tests upon the various materials. In addition to the usual tensile properties, the behavior of the material under several other conditions of testing was determined, the tests chosen being those which, it was felt, might possibly throw some light upon the reason for the character of the fracture resulting from the "nick-bend" method of testing. The resistance to shock was determined by the single-blow notched-bar impact test, the Izod machine being used since this permits of several tests being made upon a single specimen; the Eden-Foster method was employed for determining the behavior under repeated impact. The special tension test given in Table III was carried out upon specimens in which the reduction of the bar to a diameter of 0.505 in. was made at only one point along the length, by means of a 60-deg. notch. The general character of results obtained in such a test are, of course, well known. They have been included in the table primarily for comparison with the tensile properties as ordinarily determined, the nature of the fracture resulting under these conditions being of most importance so far as the present investigation is concerned.

TABLE II.—COMPOSITION OF WROUGHT IRONS USED.

Specimen.	Elements Determined.				
	Carbon, per cent.	Manganese, per cent.	Phosphorus, per cent.	Sulfur, per cent.	Silicon, per cent.
A 1	0.04	0.046	0.136	0.025	0.265
A 2	0.03	0.051	0.139	0.022	0.25
A 3	0.04	0.114	0.132	0.027	0.09
B 1	0.03	0.031	0.083	0.015	0.13
B 2	0.01	0.030	0.126	0.016	0.16
B 3	0.02	0.080	0.129	0.017	0.10
C	0.03	0.028	0.114	0.023	0.17
D	0.07	0.025	0.082	0.015	0.10
E	0.04	0.031	0.103	0.023	0.22

Some of the variations in the impact-resistance properties to be noted for the same specimens in Table III are undoubtedly to be attributed to variations in the relation between the location of the notch on the specimen with respect to the arrangement of the slag threads within.

Structure.—Macrographs showing the gross structure of the different grades of iron are given in Figs. 4 to 12, inclusive. In all cases, the finely ground section was etched with an aqueous solution of ammonium persulfate. Concentrated hydrochloric acid was also used, but on the whole its use was not so convenient nor successful as the ammonium persulfate. This reagent may be considered as a weak acid, the action of which is intensified by oxygen. The method of "piling" is plainly shown in the transverse sections. The conspicuous white streaks may be considered in most cases as the steel-bearing portions of the iron. The position of the notch with respect to the macrostructure can be easily determined since the notch is in the same relative position in all the specimens.

METHODS OF FRACTURING AND RESULTS OBTAINED.

METHOD OF NOTCHING.

For nicking the bars before fracturing, a special tool was employed. This was a chisel, ground so as to produce a 60-deg. cut and having a curved edge, the curve being somewhat greater than that of the circumference of the rod which was to be nicked. In order to secure uniformity, the nicks were all made by means of the testing machine, a load of 20,000 lb. being applied upon the head of the chisel for 2 minutes. The depth of the notch produced varied slightly with the different grades of iron, from 0.129 to 0.153 in., the average depth being 0.14 in. Precautions were also taken to notch all the specimens from each of the bars on the same side so that the location of the notch with respect to the arrangement of slag threads within would be approximately the same throughout the series.

TABLE III.—MECHANICAL PROPERTIES OF WROUGHT IRONS USED.

Material.	Tensile Properties.				Special Tension Test, Notched Bar.		Notched Bar[b] Impact (Izod), Energy Absorbed,[c] ft-lb.	Repeated Impact,[d] Number of Blows, 5-lb. Hammer.
	Yield Point,[a] lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Yield Point,[a] lb. per sq. in.	Tensile Strength, lb. per sq. in.		
A 1......	36 500	51 750	30.5	41.0	......	57 000	35.5, 51.5, 38.5	21 912 (2½-in. drop) 3 422 (4-in. ")
A 2......	31 750	50 350	32.0	37.0	......	......	48, 41, 46.5	.....
A 3......	36 500	51 750	30.5	32.5	.....	59 000	37.5, 47.5, 42.5	3 022 (4-in. drop) 1 630 (4-in. ")
B 1......	33 600	49 350	36.0	50.0	50 500	58 500	46, 49.5, 47	7 070 (4-in. drop) 10 340 (4-in. ")
B 2......	37 000	50 100	35.0	51.0	.....	.....	44.5, 43.5, 45	.....
B 3......	34 500	48 000	19.5	26.5	50 000	56 000	45.5, 45.5, 62.0	702 (4-in. drop) 700 (4-in. ")
C........	37 900	51 250	38.5	55.0	55 500	60 500	55, 61, 45.5	1 980 (4-in. drop)
D........	33 750	48 500	40.5	57.0	54 500	65 600	56.5, 63, 44.5	1 468 (4-in. drop) 660 (4-in. ")
E........	28 500	46 750	11.0	15.0	35 500	40 500	40, 30, 34.5	306 (4-in. drop) 532 (4-in. ")
					36 000	42 000	31.5, 25.5, 35.5	1 468 (4-in. ") 726 (4-in. ")

[a] From stress graph: Amsler testing machine was used with the usual 0.505-in. tension test specimens.

[b] Triple-notched specimens (1 cm.^{2} (0.394 by 0.394-in.) cross-section, 45-deg. V notch 0.079-in. deep) were used, the notches being arranged on three sides of the specimen. Hence the relationship of notch to orientation of slag threads varied in each specimen. The capacity of the Izod pendulum machine was 120 ft-lb.

[c] None of the specimens fractured completely upon impact.

[d] Eden-Foster machine was used, the specimens being 6½ in. long, ½ in. in diameter with a round filleted notch 0.05 in. deep.

METHODS OF FRACTURING.

The following methods were used for fracturing the bars after notching, as described above:

Transverse Bend.—The 6 in. specimen, symmetrically supported on a 4-in. span, was fractured in the Amsler testing machine by having a cylindrical-nosed "pin" approximately 0.8 in. (2 cm.) thick forced into it until fracture occurred or the bent specimen could be forced completely through the space between the supports (4 in.).

Upright Bend.—The notched 6-in. specimen, after having been given a slight preliminary bend, was supported on end between the jaws of the Amsler testing machine and slowly compressed lengthwise until fracture occurred, approximately 3 minutes being required in the operation. A few of the specimens were also given the preliminary bend before being notched. However, no significant differences in the fractures resulting upon lengthwise compression could be detected in such specimens as compared with those which were notched before being given the preliminary bend.

Upright Bend, Second Method.—The test was carried out as above except that the forging press was used for applying the load, two applications of the load being necessary. The slightly bent specimen was adjusted between the jaws of the press and then suddenly compressed, less than one second being required for the compression. It was necessary to readjust the partially fractured specimen for the second compression.

Impact, Hammer Blows.—The 6-in. specimen was inserted up to the notch in a hole only very slightly larger in diameter than the specimen in a heavy anvil and broken by means of blows from a 10-lb. sledge hammer applied on the projecting end on the side containing the notch. The number of blows necessary to produce fracture varied from 3 to 7 with the different specimens.

Impact, Single Blow.—The specimen, with the notched side upward, was inserted up to the notch in a hole in a heavy anvil and a 50-lb. iron block allowed to fall from a height of 9 ft. upon the projecting end. In addition to the specimens which had been notched in the usual manner, as previously described, duplicate specimens of all the grades, which had been given in the lathe a complete circumferential notch of the same average depth as in the other method of notching, were subjected to the drop test.

RESULTS.

The characteristic features of the fractures produced by breaking nicked specimens of the various grades of iron under different conditions have been summarized by means of photographs in Figs. 4 to 12, inclusive. For purposes of comparison, Figs. 1, 2 and 3 showing the fracture of the different irons when subjected to the various mechanical tests: tension, impact, and repeated impact, have been included. In none of the ordinary tension or the notched-bar tension specimens (Fig. 1) was there any indication of a crystallin structure revealed in the fracture. In the notched-bar impact (Izod) fracture, only very slight indications of crystallinity were shown by a few of the specimens (Fig. 2). Of the specimens fractured by repeated impact (Eden-Foster test) only one gave any indication of crystallin spots in the fracture. It may be concluded, then, that the "nick-bend" test, as employed for the testing of wrought iron, is intended to reveal certain characteristics of the material which the usual mechanical tests fail almost entirely to indicate.

The fractures produced in nicked bars by lengthwise compression in the testing machine and in the forging press were found not to differ in any essential respects from those resulting from simple transverse bending. Hence, in order to conserve space in reproduction, photographs representative of these methods of fracturing have not been included in the sets given.

In all cases, except in Fig. 12, the photographs have been arranged so that the left-hand edge of the figure represents the side of the bar which was notched, or, in the case of the circumferentially notched specimens, the side upon which the load was applied. The photographs were taken so as to show all the specimens at natural size. In many cases, however, it was necessary to tilt the sample so as to reveal clearly the characteristic features so that some distortion occurred. It will be evident even from a cursory examination of the fractures that simple transverse bending of a nicked bar of each of the nine grades of iron used was not sufficient to reveal in the fracture any significant features such as the "nick-bend" test is intended to show. The fact that impact is necessary in the production of the large conspicuous crystallin areas is evident in nearly all the figures in the fractures resulting from the use of the sledge or from the single-blow impact test. In many of the fractured specimens, two crystallin areas may be noted, one immediately beneath the notch and the other on the opposite side of the bar. This feature is also illustrated in Fig. 13 and will be considered later in greater detail.

It will also be noted in the bars fractured by the single-blow impact test that the extent of the notch around the specimen had a very pronounced effect upon the character of the fracture. In none of the specimens having the circumferential notch was there any pronounced crystallinity in the fracture when broken by the drop test.

Fig. 13 has been included as an illustration of a series of fractures produced in the commercial testing of wrought iron. They were chosen from a considerable number of specimens submitted to the Bureau of Standards for examination. One important feature to be noted in many of the fractures is the location of a very conspicuous crystallin area on the side of the bar opposite to the notch.

In Fig. 14 is shown the appearance of the fracture produced in one of the wrought irons after a preliminary stretching of the bar. It has been suggested[1] that this condition has an important effect upon the character of the fracture resulting in the "nick-bend" test. Specimens, 18 in. long, representative of bars A 1, A 3, C and D were permanently stretched in the testing machine in amounts varying from 8 to 25 per cent, as measured on the central 2-in. length of the specimen. Six-in. specimens were then cut from these stretched bars and after nicking were fractured by transverse bending and by the single-blow impact test. The results shown in Fig. 14 for material C are typical of the fractures obtained for all. The cold working which the bar received in the preliminary stretching increased the tensile strength to a very marked extent so that a much severer blow was necessary in order to fracture the bar. For specimen C (Fig. 14) a fall of 13 ft. for the 50-lb. weight was necessary in order to fracture the specimen, whereas for the unstretched specimen a blow from the same weight from 9 ft. was sufficient. Aside from this, no other differences were noted, the characteristic features of the fracture were not essentially changed.[2]

DISCUSSION.

It is evident from the results summarized above that the rate at which the load is applied in fracturing the notched bars is of very great importance, and appears to be the predominating factor which determines the character of the fracture. Each of the nine grades of iron when stressed slowly, or at a moderate rate, broke without showing any marked tendency toward crystallinity; whereas, when fractured by impact, either by sledge blows or by the drop test, the appearance of the fracture was very materially changed and all of the specimens showed crystallin areas the size of which varied with the different grades of iron.

The character of the nick, however, appears to be of almost equal importance. Specimens representative of all the nine different

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[1] Private communication from one of the manufacturers supplying material.

[2] The results obtained are apparently not in accordance with that published by Jones and Greaves, *Proceedings*, Inst. Civil Engineers (British), Vol. 211 (1920–21), who report that the general effect of over-strain is to reduce the impact figure.

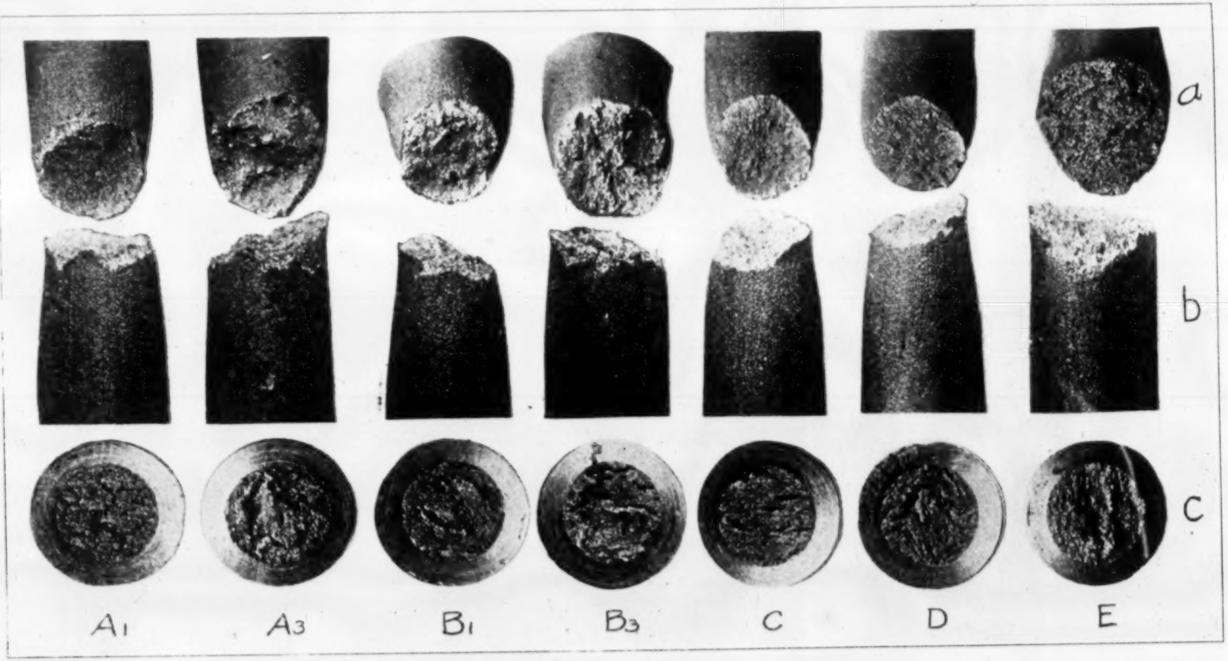


FIG. 1.—Typical Fractures of the Various Grades of Wrought Iron Broken in Tension.
(*a*) Oblique (45 deg.) view of the end of the broken tension specimen (× 1½).
(*b*) Side view of the specimens shown in (*a*) (× 1½).
(*c*) End view of fractured notched-tension specimens (× 1).

No crystallinity is to be observed in the fractures of any of the specimens.

grades of iron when notched circumferentially, that is, completely around the bar, and subjected to the drop test, broke without showing crystallin areas to any noticeable extent. The distribution of the stress across the section of the bar is, of course, very materially changed by the presence of a notch on both sides of the specimen; hence the change in the appearance of the fracture. The fractures obtained in this manner closely resembled those resulting from the notched-bar tension test.

Mention has already been made of the presence of crystallin areas of two different types in many of the impact fractures, one on the tension side of the stressed specimen and the other near the compression side. Although the two types appear similar in a photograph, to the eye there are very distinct and characteristic differences to be noted. The "compression" areas, although crystallin in appearance, lack the rough sharp contour and hence much of the sparkling appearance of the "tension" areas. The softer sheen of the compression areas, taken in connection with the fact that they are best seen when viewed at certain definite angles, suggested an appearance characteristic of a surface covered with flattened scales.

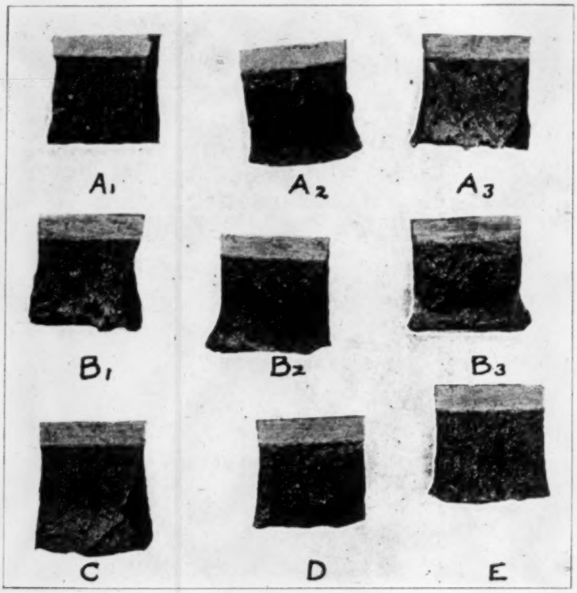


FIG. 2.—Typical Fractures of Wrought Iron Broken by the Notched-Bar Impact (Izod) Test (× $1\frac{1}{2}$).

Only a few of the specimens show any evidence of crystallin areas in the fracture.

The real difference between these two types of crystallin areas is best shown by an examination of the microstructure as illustrated in Fig. 15 which represents longitudinal sections of specimens perpendicular to the face of the fracture. It will be noted that in the "tension" crystallin areas, the fracture occurred as a trans-crystallin break, that is, along cleavage planes, without any deformation of the individual crystals. The direction of the cleavage of several adjacent crystals was found to coincide frequently, thus giving rise to larger "facets." The contour of the surface resulting from this type of rupture presents a rough jagged outline along any right section taken through it. These features in the fracture of a ductile metal are generally considered characteristic of a break occurring very suddenly, usually by impact. In the fibrous portion of the fracture, for example, between the two crystallin areas, the crystals of iron were severely deformed by tension, each being drawn out to a fine point at the place of rupture. Evidently the stress causing rupture in this part of the bar acted at a much slower rate than in the portion which gave the crystallin break just described. The appearance of the metal in the compression crystallin areas shows that the grains were subjected to very severe compression previous to the final tensile break. Many of the grains were flattened perpendicularly to the length of the bar and others not so severely distorted in shape showed numerous prominent slip bands resulting from compressive stress (Figs. 5 *c* and ***d***). In

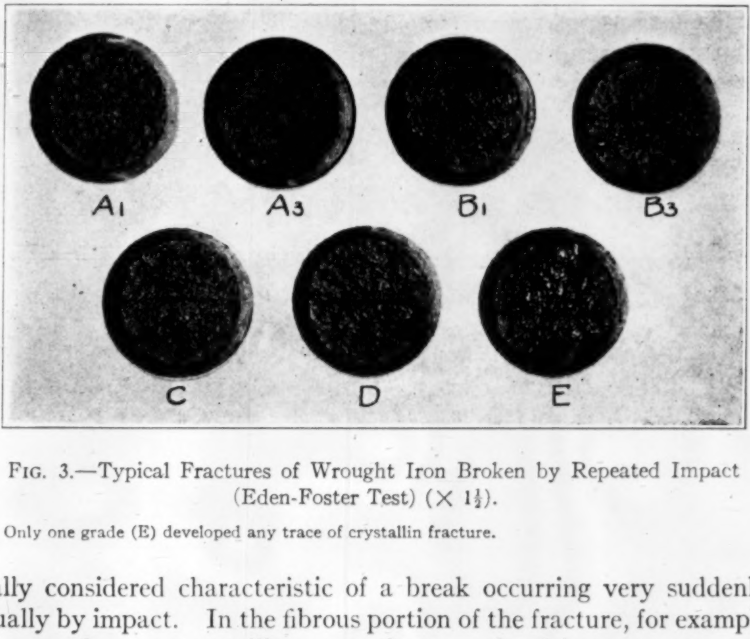


FIG. 3.—Typical Fractures of Wrought Iron Broken by Repeated Impact (Eden-Foster Test) (× 1½).

Only one grade (E) developed any trace of crystallin fracture.

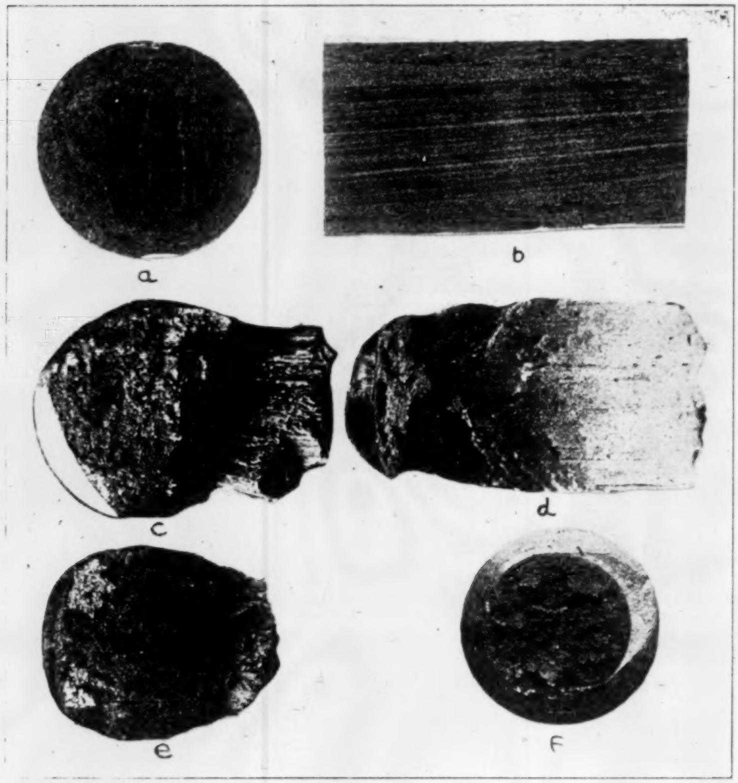


FIG. 4.—Typical Results Obtained by the Nick-Bend Upon Wrought Iron, Specimen A 1 (× 1).

(*a*) Transverse section, etched with ammonium persulfate to reveal the macrostructure.

(*b*) Longitudinal section, etched with ammonium persulfate.

(*c*) Fracture produced in the nicked bar by transverse bending, the load being applied opposite the notch and the specimen supported 2 in. each side of the notch.

(*d*) Fracture of a nicked bar broken by blows from a 10-lb. sledge.

(*e*) Fracture of a bar nicked on one side and broken by the drop test (50-lb., 9 ft.).

(*f*) Fracture of a specimen with a circumferential notch broken as in (*e*).

The notched side of the bar is toward the left, in (*f*) the blow was received from the left.

most cases, the bar subjected to the drop test did not fracture completely. It was necessary to complete the break, usually by hammer and vise, whereupon the compressive crystallin area was revealed. The characteristic scaly appearance of these areas appears to be the direct result of the severe compression the crystals were subjected to during the period of impact rather than to any characteristic property of the metal as it exists in the unstressed bar. The fact that the location of the notch along the circumference of the bar determines the location of the two types of crystallin areas is also very significant. It is evident then that the two types of crystallin areas originate in an entirely different manner and should not be regarded as indicative of the same characteristic of the metal.

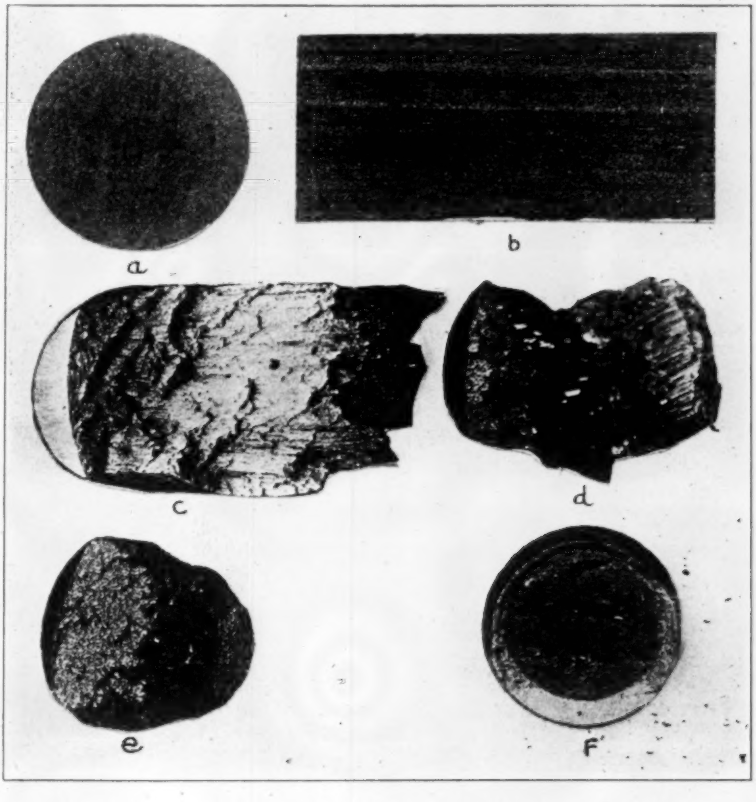


FIG. 5.—Typical Results Obtained by the Nick-Bend Test Upon Wrought Iron, Specimen A 2 (× 1).

See legend of Fig. 4.

In general, there appeared to be no definite relationship between the location and character of the crystallin areas in the fracture and the streaks which constitute the wrought-iron structure. However, one of the specimens, A 3 (Fig. 6), offered some evidence which suggests that the presence of prominent steel streaks within wrought iron do affect to some extent the character of the break. The three prominent areas (Fig. 6*a*) seen in the cross-section of Specimen A 3 were found to have the characteristic microstructure of low-carbon steel. In nearly all the fractures of this bar, three areas corresponding to these streaks could be noted, and in the fractures resulting from impact stresses, these areas were largely crystallin in appearance. Likewise, it may

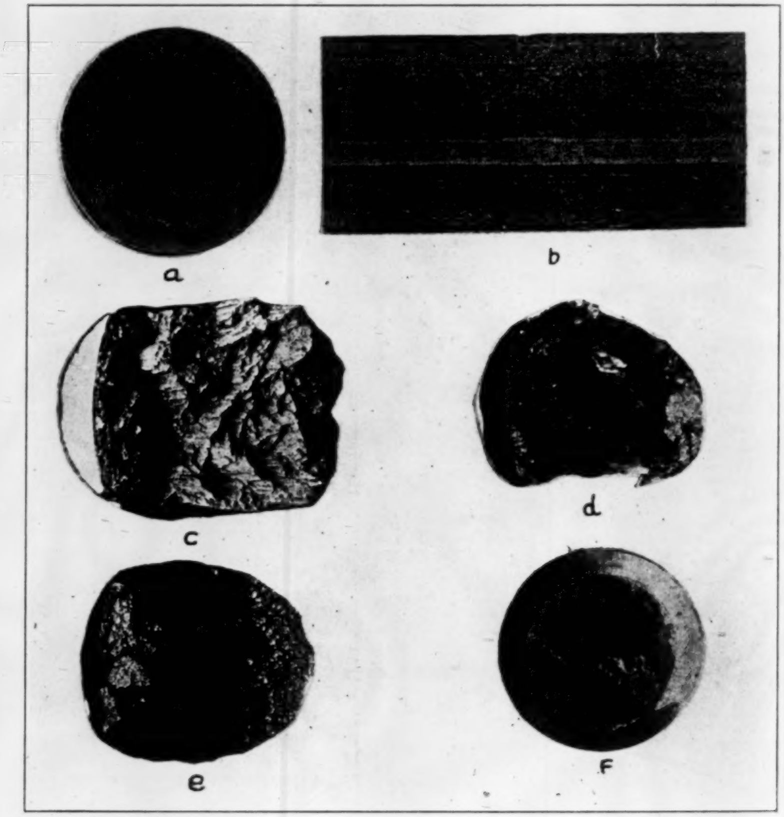


FIG. 6.—Typical Results Obtained by the Nick-Bend Test Upon Wrought Iron, Specimen A 3 (× 1).

See legend of Fig. 4.
Note the "compression" crystallin area in (*d*) and (*e*).

be noted in B_1 (Fig. 7) that the location and shape of the crystallin areas resulting from impact, particularly by the sledge, appear to have been determined to a noticeable extent by the white (steel-bearing) streaks to be seen in the cross-section of this bar. This factor, as contributory to the character of the fracture, is of only minor importance, however, as compared to the character and distribution of the stress causing rupture.

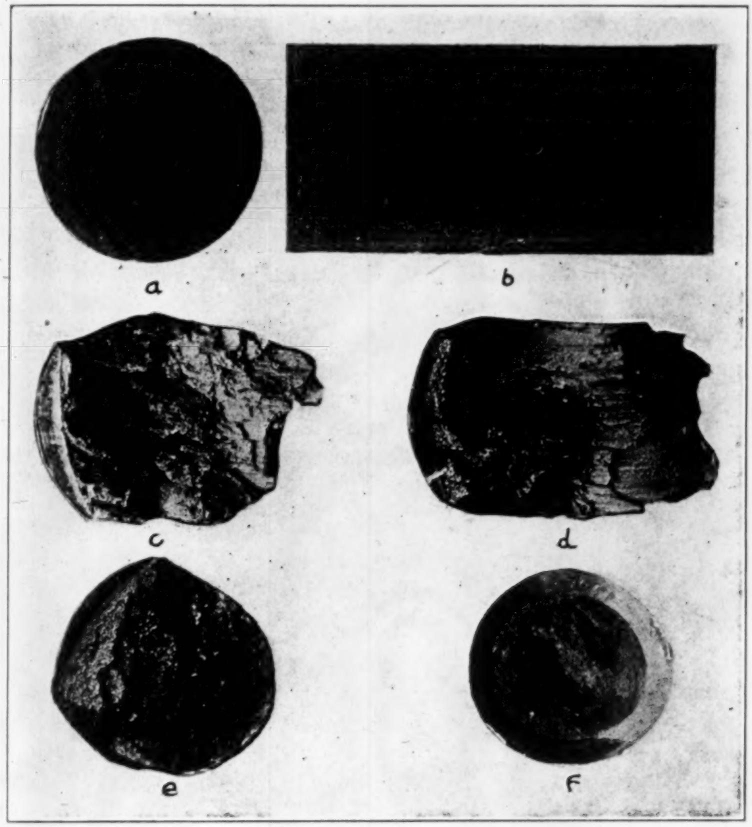


FIG. 7.—Typical Results Obtained by the Nick-Bend Test Upon Wrought Iron, Specimen B 1 (× 1).

See legend of Fig. 4.

The size of the slag threads within the iron and their distribution with respect to the notch often has an important bearing on the fracture. The prominent slag threads break up the continuity of the metal and thus tend to limit the extent of any crystallin fracture, once started. Splitting of the bar along prominent slag lines during fracturing was not unusual. The large conspicuous crystallin areas to be noted in Specimen D (Fig. 11) when broken under impact are undoubtedly partially accounted for by the fact that the slag threads were small and well distributed in this material. The chemical analysis showed this specimen to be the highest in carbon of any. This factor probably also contributed considerably to the behavior of this material under impact stresses.

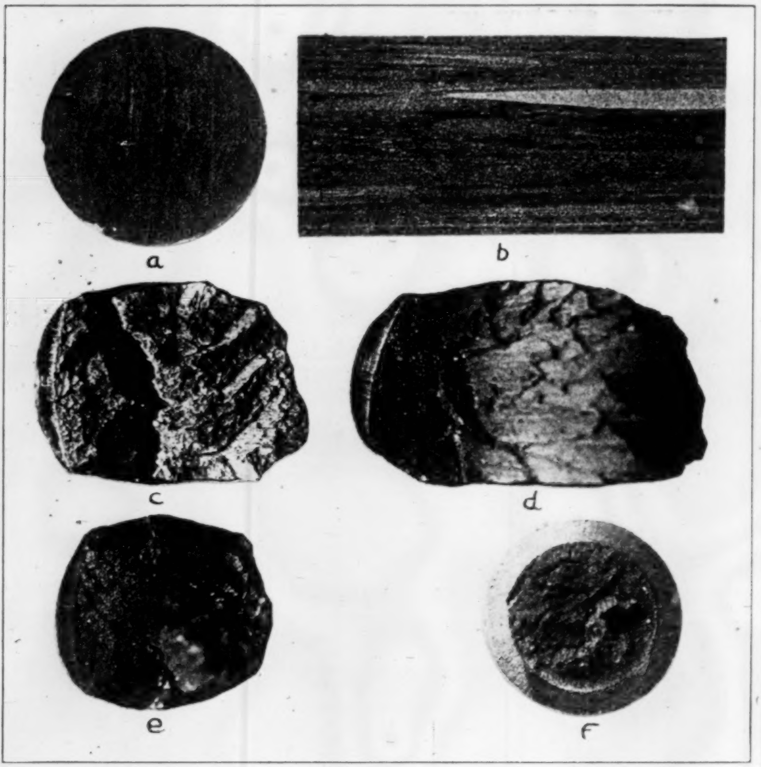


FIG. 8.—Typical Results Obtained by the Nick-Bend Test Upon Wrought Iron, Specimen B 2 (× 1).

See legend of Fig. 4.

The behavior of Specimen E (Fig. 12) when broken by impact after nicking is of interest in that it suggests other factors which may affect the appearance of the fracture. This material represented an intermediate stage in the manufacture of wrought iron and contained relatively thick plates of slag arranged like the leaves in a book. When nicked and fractured on the edge of the "leaves," conspicuous crystallin areas resulted; whereas when broken under the same conditions, except that the nick was made at right angles to the first, that is, on the flat side of the "leaves," no crystallinity resulted. It should be noted, however, that the "depth" of the cross-section of the specimen was not the same in both cases—a fact which probably had some effect upon the behavior of the sample.

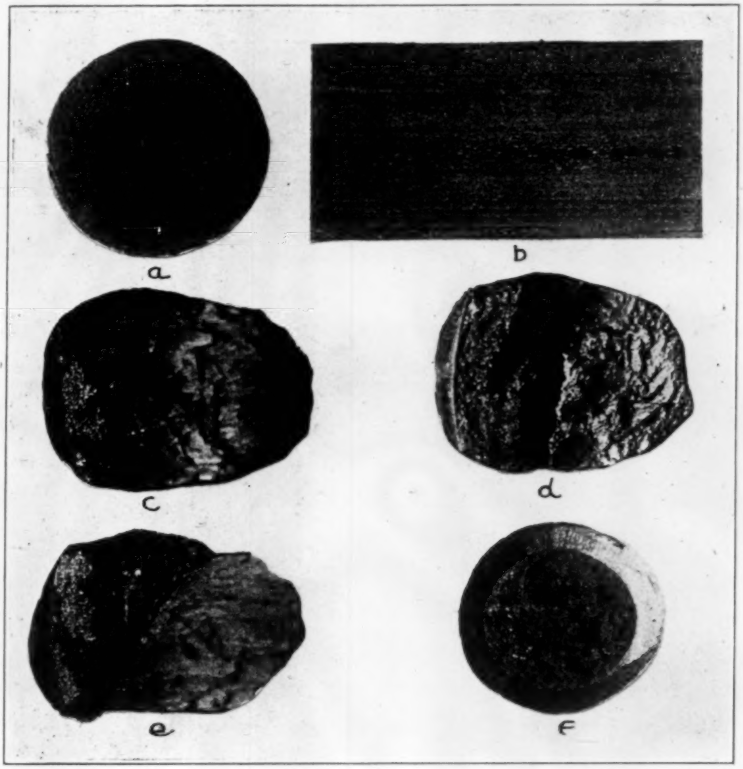


FIG. 9.—Typical Results Obtained by the Nick-Bend Test Upon Wrought Iron, Specimen B 3 (× 1).

See legend of Fig. 4.

SUMMARY AND CONCLUSIONS.

The material examined represents the finished product of four different manufacturers and an intermediate stage in wrought-iron manufacture from a fifth source, nine grades in all being tested.

The methods used for fracturing the nicked bars varied from a slowly applied transverse bending stress to a severe single-blow impact stress. This range is permitted by most current American specifications. Although the investigation has not been comprehensive enough to furnish answers to all the questions which may arise concerning the "nick-bend" test for wrought iron, the results obtained are definite enough to permit certain conclusions being drawn and to warrant certain recommendations concerning the test.

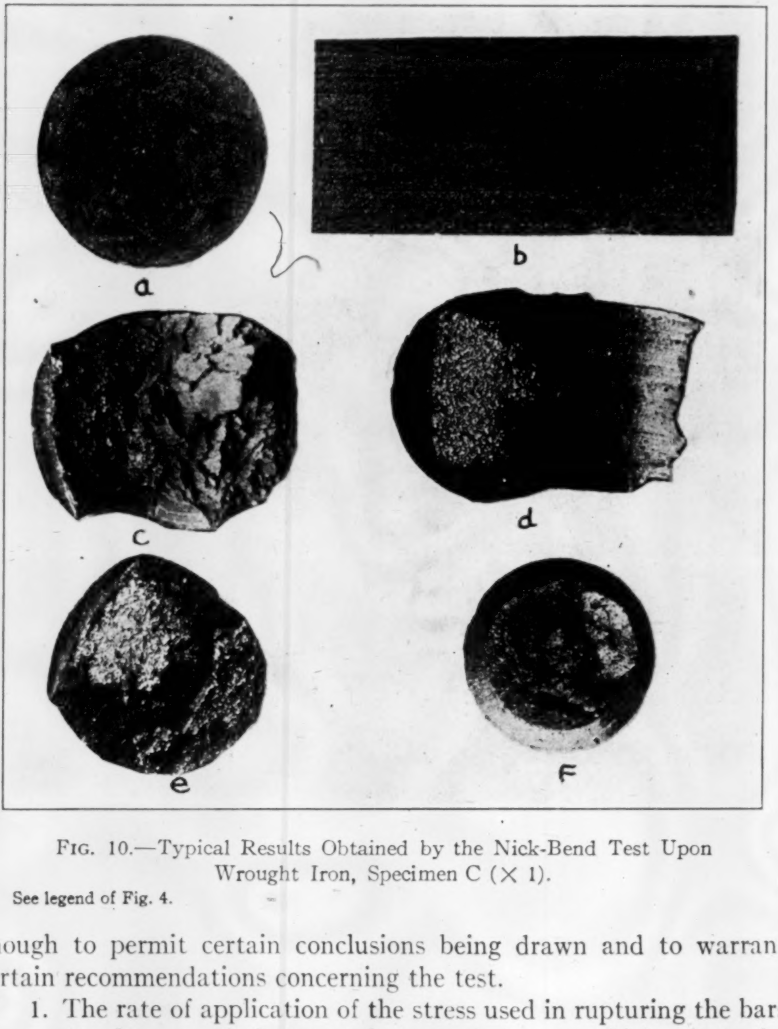


FIG. 10.—Typical Results Obtained by the Nick-Bend Test Upon Wrought Iron, Specimen C (× 1).

See legend of Fig. 4.

1. The rate of application of the stress used in rupturing the bars appears to be one of the most important factors which affect the results of the test, that is, the appearance of the fracture. All of the grades tested successfully passed inspection when slowly or moderately

stressed. Under shock, however, all showed crystallinity in the fracture, several to an extent which would cause rejection. The results obtained suggest the desirability for defining more strictly the conditions for carrying out this test than is the case in many current specifications. The ordinary methods used in mechanical testing fail almost entirely to give any indication of the features shown by the nick-bend test.

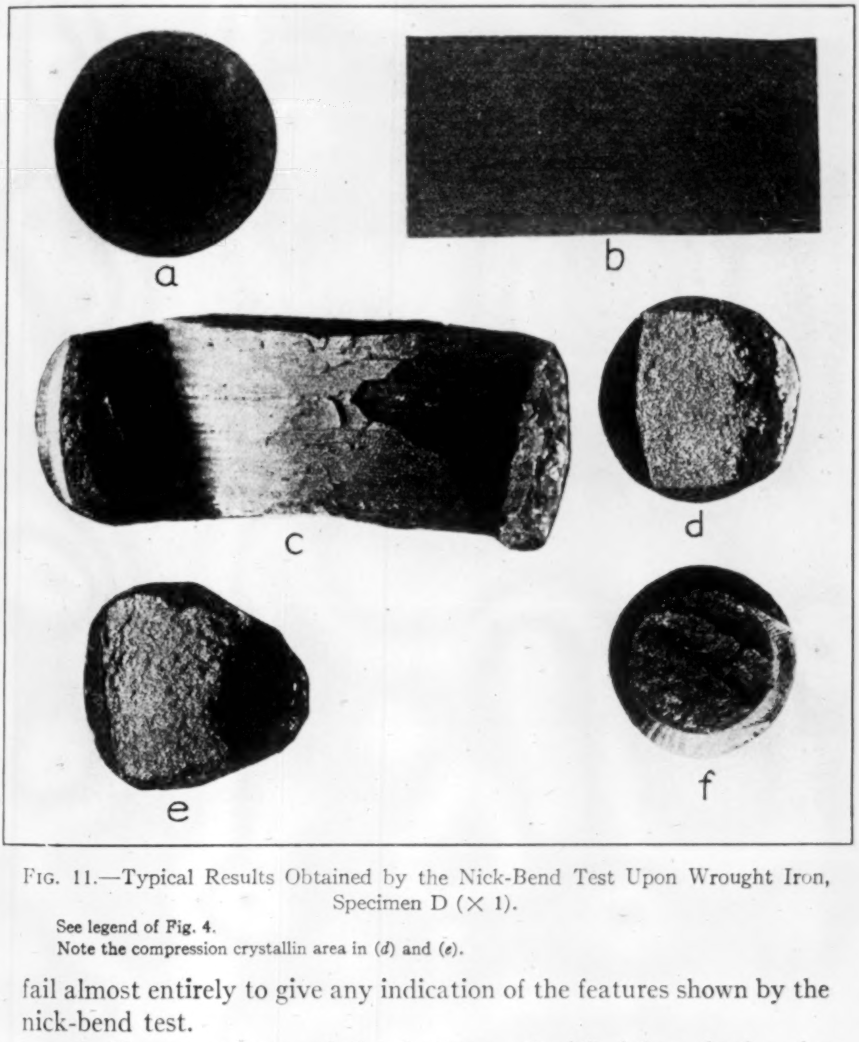


FIG. 11.—Typical Results Obtained by the Nick-Bend Test Upon Wrought Iron, Specimen D (× 1).

See legend of Fig. 4.
Note the compression crystallin area in (*d*) and (*e*).

2. The appearance of the fractures of nicked bars broken by impact is dependent upon the character, particularly the extent, of the notch to a very marked degree. The depth and length of the notch relative to the specimen tested should be carefully regulated. This

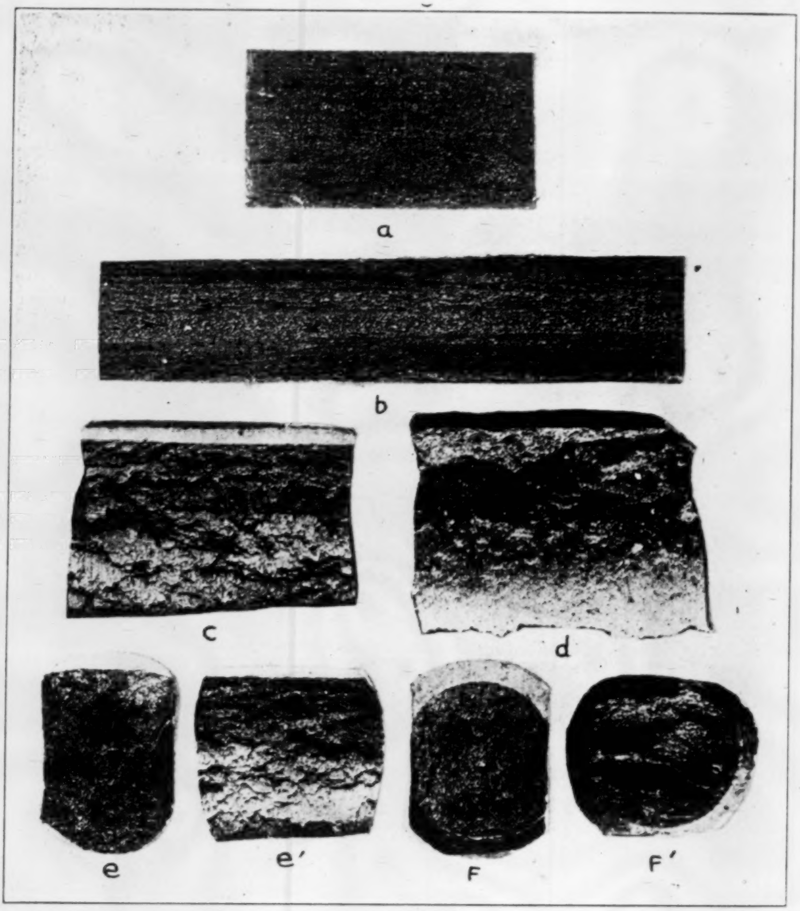


FIG. 12.—Typical Results Obtained by the Nick-Bend Test Upon Wrought Iron, Specimen E (× 1).

(*a*) Cross-section of a bar etched with ammonium persulfate to reveal the macrostructure.

(*b*) Longitudinal section of a bar etched as in (*a*).

(*c*) Fracture produced by a transverse bend of a notched bar, the load being applied opposite the notch and the specimen supported 2 in. each side of the notch.

(*d*) Fracture of a nicked bar produced by a 10-lb. sledge hammer. Note the small isolated crystallin spots.

(*e*) Fracture produced by the drop test (50-lb., 9 ft.) on a specimen nicked on the "edge" of the plate.
Note the crystallin area on the tension side.

(*e′*) Fracture of a bar similar to (*e*) which was notched on the flat side of the plate.
Note the almost complete absence of crystallinity.

(*f*) Fracture of a bar similar to (*e*), notched completely around. Note the absence of crystallin areas.

(*f′*) Fracture of a bar similar to (*f*), the blow was so as to bend the specimen as in (*e′*).

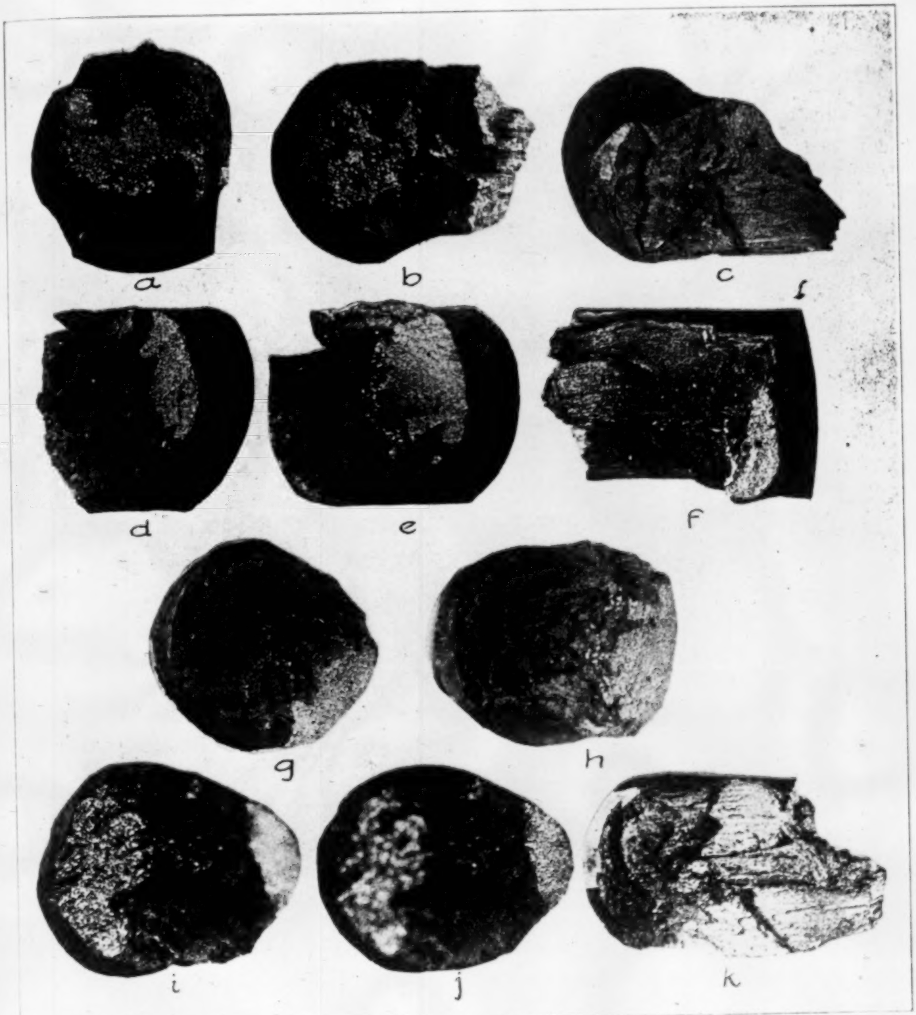


FIG. 13.—Typical Fracture of Wrought Iron Broken by the Nick-Bend Test, Submitted by a Commercial Laboratory (× 1). The notch in each case is at the left.

(*a*) 1-in. bar nicked and broken by sledge blows.

(*b*) Specimen similar to (*a*) broken by transverse bending, the specimen (notch downward) being supported at the ends and loaded above the notch. Note the "tension" and the "compression" crystallin areas in both (*a*) and (*b*).

(*c*) Specimen similar to (*a*) fractured by lengthwise compression by means of *light* blows from a steam hammer. The fracture was largely fibrous.

(*d*) Fracture of a nicked bar produced by lengthwise compression in a testing machine.

(*e*) Specimen similar to (*d*) broken by sledge blows. Note the absence of crystallinity on the tension side and the very prominent crystallin area on the compression side of (*d*) and (*e*).

(*f*) Side view of a nicked specimen broken by lengthwise compression in the testing machine. Note the "compression" crystallin area.

(*g*) Specimen broken by lengthwise compression in the testing machine.

(*h*) Specimen broken by light sledge blows. Note the conspicuous "compression" crystallin area in each case and the complete absence of crystallinity on the tension side of the bar.

(*i*), (*j*) Two views, at different focus, of a nicked specimen broken as by sledge blows. Note both "tension" and "compression" crystallin areas.

(*k*) Same specimen as (*i*), broken by lengthwise compression. Note the fibrous character of the fracture.

can be more readily done by notching in the press with a special chisel than by hand. Specimens having complete circumferential notches, when broken by severe impact, showed very little crystallinity, whereas, the same specimen notched on one side only often showed very large crystallin patches.

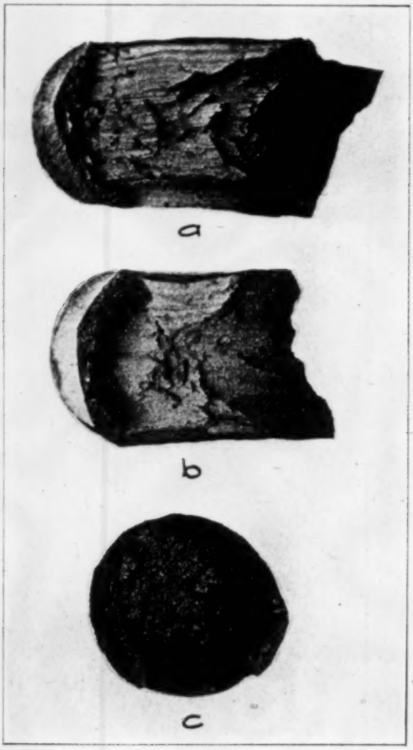


FIG. 14.—Fractures Resulting from the Nick-Bend Test of Wrought Iron (Grade C), Previously Deformed by Stretching (× 1).

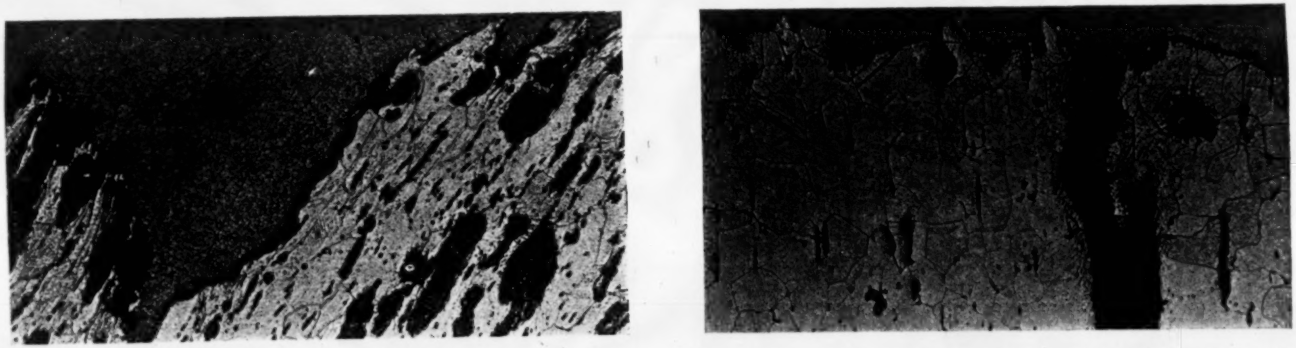
(*a*) The nicked specimen was broken by transverse bending.

(*b*) Similar specimen broken by the drop test (50-lb., 9 ft.).

(*c*) Similar specimen broken by the drop test (50-lb., 13 ft.)

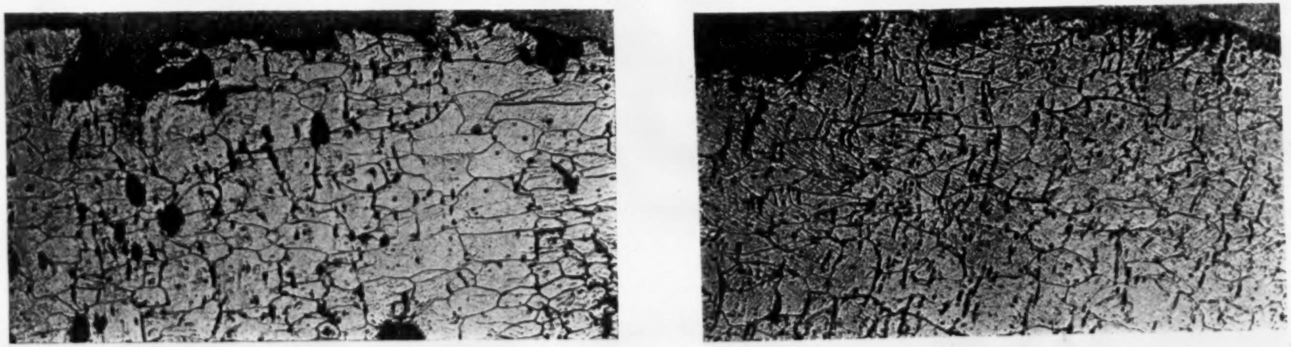
Compare with Fig. 10.

3. There are two distinct types of crystallin areas produced in the "nick-bend" test of wrought iron. The one near the tension side of the stressed bar is the direct result of the stress applied and indicates certain characteristics of the material. The crystallin area on the compression side, which is often the larger and more conspicuous of the two, depends for its formation upon the preliminary permanent



(*a*) Fibrous portion of the fracture of Specimen A (Fig. 4).
Note how the crystals were drawn out to fine points.

(*b*) Crystallin area on the tensile side of the Stressed Specimen C (Fig. 10).
Note the sharp straight breaks across the crystals, without any appreciable deformation of the crystal.



(*c*) Crystallin area on the compression side of Specimen A (Fig. 4).
Note the pronounced flattening of the grains at right angles to the length of the bar.

(*d*) Crystallin area on the compression side of Specimen C (Fig. 10).
Note the flattening of the grains, also the numerous slip planes within the grains, along which fracture might take place.

FIG. 15.—Microstructure of Wrought Iron Corresponding to the Different Fractures Produced in the Nick-Bend Test (× 100).
All sections are longitudinal and were etched with a 5-per-cent alcoholic solution of picric acid.

distortion in compression of the crystals in this part of the specimen, and does not necessarily indicate any characteristic features of the unstressed material.

4. Prominent steel-bearing streaks in wrought iron appear to favor to some extent the formation of crystallin areas when fractured under impact, although crystallin areas are not necessarily indicative of "steel" in the iron. Prominent slag streaks often permit longitudinal separations to occur during testing, thus giving rise to a fibrous appearance. The absence of such streaks or the presence of small and uniformly distributed streaks appears to favor the production of larger crystallin areas upon impact.

5. In the testing of plates or flat bars by the nick-bend test the relation of the location of the notch with respect to the slag plates ought to be specified, that is, whether upon the edge or the flat side of the plate.

6. Bars which had been permanently stretched before being subjected to the nick-bend test gave no indications so far as the characteristic features of the fracture were concerned of the preliminary treatment to which they had been subjected. The cold work very materially strengthened such bars, however, so that a much severer blow was necessary in the fracturing of such specimens than before stretching.

7. The present investigation was carried out upon bars of uniform size, 1 in. in diameter. An additional study of other sizes, preferably larger ones, would undoubtedly throw further light upon the results of the nick-bend test and their interpretation. Likewise the testing of bars of abnormal composition, particularly irons high in phosphorus, would give results of value regarding this test. Variations in the method of gripping the specimen, relative to the notch, may also merit some attention. The present study gives no information on these points.

THE PHYSICS OF CAST IRON AND ITS BEARING ON ALL CAST-IRON PRODUCTS AND SPECIFICATIONS FOR CAST IRON.

By William R. Webster.[1]

Our Committee on Cast Iron has always had difficult problems to contend with, as a large part of its work has been on new lines and there were at the start very few reliable data that could be used in formulating its specifications. But at this time I believe that sufficient reliable data have been accumulated from the general use of the present specifications of the committee to enable the committee to make improvements in and additions to our present specifications, provided that proper cooperation can be secured with the blast furnace men, the iron foundries, and the consulting engineers representing both the producers and the consumers. It is with the hope of securing such cooperation and improvements in our specifications that the present paper is presented.

A good starting point for consideration is the early work of the American Institute of Mining Engineers on cast iron, as they covered such a wide field of work that had a most important bearing on the more recent work of our Committee on Cast Iron. The Institute's papers and discussions on the Metallurgy and Physics of Cast Iron, starting in the early nineties and continuing over several years, undoubtedly paved the way for our present specifications for the grading and sale of pig iron by its chemical composition instead of by fracture. Having taken an active part in this early work of the Institute, the writer considers that a short summary of this work with its relations to the work of the American Society for Testing Materials and some suggestions for further work on our cast iron specifications to bring them up to date will be timely and of interest to our members. It is hoped that this course will bring out in discussion and other papers additional new matter that will be of great service to our Committee on Cast Iron.

At the Florida meeting of the American Institute of Mining Engineers in March of 1895, I presented a brief Note on a Proposed Scheme for the Study of the Physics of Cast Iron, the former papers on the tests of cast iron and details of foundry practice having shown that the time was ripe to attempt the solution of some of the many problems that the iron foundries had to contend with. In order to bring about a complete and systematic discussion I tabulated in convenient form some of the most important matters as "Suggested Lines for Discussion and Investigation" on the same general plan as had been used with such good results in a similar discussion on the Physics of Steel. This I now repeat for convenience of reference.

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[1] Consulting Engineer, Philadelphia.

SUGGESTED LINES FOR DISCUSSION AND INVESTIGATION.

I. Correspondence between chemical composition and melting-point, fluidity, shrinkage, fracture, chill, micro-structure, and other physical properties.

II. Influence of:

1. Cupola-mixture, use of steel and other scrap, oxidized or clean material.
2. Manner of melting, flux, etc.
3. Casting temperature.
4. Manner of handling melted metal and method of casting.
5. Size and form of casting.
6. Kind of mold, green sand (under different conditions of ramming, amount of moisture, and skin-dried), dry sand, loam, and chills.
7. Rate and mode of cooling castings.
8. Manner and temperature of heating for annealing.
9. Additions of nickel or aluminum.

on

- A. Fracture.
- B. Micro-structure.
- C. Physical properties.
- D. Shrinkage.
- E. Chill.
- F. Residual stress.
- G. Condition and quantity of carbon and other elements.

III. Segregation as affected by: 1. Composition; 2. Casting temperature; 3. Rate of cooling; 4. Size and shape of casting.

IV. Blow-holes, their volume and position as affected by: 1. Composition; 2. Casting temperature; 3. Casting pressure; 4. Rate of cooling; 5. Size and shape of casting; 6. Special additions.

The discussions and papers that followed were most encouraging, exceeding our expectations and continuing over several years, but there were not sufficient data to arrive at any definite results although many valuable suggestions were made. In 1904 at the annual meeting of the Institute, on the request of the Council to revive the interesting discussions on the Physics of Cast Iron, I brought up again the former plan for these discussions, with the suggestion that they be brought up to date and that those who had been working on specifications for cast iron, the methods of testing, etc., should present such specifications for discussion and give the reasons and methods which led to their adoption. I also called particular attention to the following:

> "A point of peculiar modern importance is the classification of pig iron by its chemical analysis, which involves, of course, the relation between its chemical constitution and physical properties. Since our former discussion, the use of machine-cast sandless pig iron has forced the foundrymen to give up, to a large extent, the grading of the pig by fracture and to depend on the chemical

> analysis alone. This, in turn, has brought them to rely on the relation between the chemical constitution of the mixture and the physical properties of the finished casting. They are also now more inclined to discuss the information they have acquired on these subjects, and to feel that they will be well repaid by the assistance received from such an interchange of ideas."

The discussions and papers that followed were most satisfactory and showed that decided advances had been made in the metallurgy of cast iron during the intervening nine years. Suggestions were made to grade pig iron by its chemical composition instead of by fracture and freely discussed without arriving at any definite conclusions.

Mr. Richard Moldenke gave at that time a very interesting and instructive paper in which he carefully reviewed my "suggested lines for discussion and investigation," going into the subject very thoroughly.[1] This will be of unusual interest to our Committee on Cast Iron, as Mr. Moldenke, the chairman of that committee, has recently, at my request, reviewed my paper referred to above in order to bring it up to date at this time. This review is appended to the present paper.

He has also taken up some other matters of general interest and importance that we discussed. It is very gratifying that the original suggested lines for discussion are yet in working order, but undoubtedly great improvements can be made in them when we take into consideration the results that can now be obtained by the use of the electric furnace and the advances that have been made in the metallurgy of cast iron and malleable irons. New matter on these subjects will undoubtedly be brought out in our proposed discussions before this Society that will be of service to both the producers and consumers using the specifications of the Society, which should also be brought up to date and made to cover all grades of material.

The Standard Specifications for Foundry Pig Iron (A 43 - 09) of the American Society for Testing Materials referred to above have now been in general use for some seventeen years[2] and have given excellent results. Yet there are no definite statements in the specifications of the chemical composition of the foundry pig iron that would guide and assist the foundrymen in making light castings, medium castings, heavy castings or malleable iron; all that they have given the foundryman is a convenient code for writing out a prescription in code words to the blast furnace man giving the chemical composition of the irons which he considers will best meet his requirements. Under these conditions it is not at all surprising that the orders from foundries making the same grade and weight of castings vary considerably in their chemical requirements and cause the blast furnace men unnecessary trouble, as they are required to make several grades of pig iron for the same class and weight of castings. This is simply a useless waste of time and money that can easily be corrected by all parties interested getting together and giving their views based on the results of actual use of the present A.S.T.M. Specifications for Foundry Pig Iron, as this would no doubt result in getting together very fair average chemical compositions of the irons used for each weight of castings, taking into account the different foundry methods in use for such work.

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[1] *Transactions*, Am. Inst. Mining Engineers, Vol. XXXV, p. 149 (1905).

[2] The specifications were first adopted in 1904 and were revised in 1909.

The problem is not as hard as it seems at first sight, for it only requires that a few of the large foundrymen shall give the chemical compositions of the pig irons they have used for each class of work. This will induce others to follow the same course. The blast furnace men have a great deal of such data on hand that will no doubt be available for getting at the proper representative results based on the use of our specifications during the past seventeen years. This is not too much to expect, and the only wonder is that it has not been done before. This course would simply be an endorsement of the general plan of our present specifications, and would put the compositions of the irons now generally called for in each class of work into standard form for ordering.

When one looks back on the excellent work of our old foundrymen, who had practically nothing to guide them but the grading of the pig iron by its fracture, we have to admit that they deserve the greatest credit for the excellent results they produced in all classes of castings. We now know in a general way the chemical compositions of the foundry pig irons they used and that for the same grade of pig iron from different districts the chemical composition varied. It would be very interesting and instructive to get this information together as a permanent record of our former foundry work and for the general use that can now be made of it at this time in connection with our present specification for foundry pig iron. Fortunately, a very large amount of foundry pig iron is still sold under the old names, but in each case the chemical compositions are given, thus combining the old and the new methods in a most satisfactory manner. In the Philadelphia district we have the following grading:

	SILICON, PER CENT.	SULFUR, PER CENT.	PHOSPHORUS, PER CENT.
No. 1 foundry..............	2.75 – 3.25	0.05 or less	0.50 – 0.80
No. 2 X....................	2.25 – 2.75	0.05 " "	0.50 – 0.80
No. 2 plain................	1.75 – 2.25	0.05 " "	0.50 – 0.80

The following is quoted from an interesting paper of Mr. Y. A. Dyer on Purchasing of Foundry Iron by Specifications,[1] in which he fully covers some of the important points referred to in the present paper and gives a very complete table on the chemical composition of the irons furnished from different districts that will be of service in the consideration of this subject:

> Each iron producing section has its own analysis specifications. However, during the world war, there was created by the committee on steel and steel products of the American Iron and Steel Institute, November 14, 1918, and approved by the President, a special foundry grading of iron equivalent to the following analyses:

		SILICON, PER CENT.	SULFUR, PER CENT.
Base	No. 1 soft	3.25 – 3.74	0.05 and under
	No. 1 foundry	2.75 – 3.24	0.05 " "
	No. 2 soft	2.25 – 2.74	0.05 " "
	No. 2 foundry	1.75 – 2.24	0.05 " "
	No. 3 foundry	1.25 – 1.74	0.05 " "
	No. 4 foundry, or forge	0.75 – 1.24	0.05 – 0.08

> No. 2 soft southern iron is equivalent to the old grading of No. 2 foundry, and in numerous instances the higher silicon, 2.25 to 2.74, is still shipped by Southern furnaces on No. 2 foundry orders. Manganese and phosphorus content are adjustable according to customary regulations peculiar to each district.
>
> Following is a fair average of grouped analyses covering pig iron production in the United States:

	SILICON, PER CENT.	SULFUR, PER CENT.	PHOSPHORUS, PER CENT.	MANGANESE, PER CENT.
Foundry:				
Northern	1.25 – 3.75	0.03 – 0.05	0.40 – 0.90	0.40 – 1.00
Eastern	1.25 – 3.75	0.03 – 0.05	0.40 – 0.90	0.40 – 1.00
Southern	1.25 – 3.75	0.03 – 0.05	0.70 – 1.50	0.20 – 0.60
Forge:				
Northern	0.75 – 1.25	0.05 – 0.08	0.40 – 0.80	
Eastern	0.75 – 1.25	0.05 – 0.08	0.40 – 0.80	
Southern	0.75 – 1.25	0.05 – 0.08	0.70 – 1.50	
Basic:				
Northern	1.00 max.	0.05 max.	0.50	0.75 – 1.50
Eastern	1.00 max.	0.05 max.	0.50	0.75 – 1.50
Southern	1.00 max.	0.05 max.	0.70 – 1.00	0.20 – 0.60
Bessemer	1.00 – 3.00	0.05 max.	0.10 max.	0.40 – 1.50
Malleable	0.75 – 1.75	0.05 max.	0.20 max.	0.40 – 1.50
Special foundry:				
Northern	1.25 – 3.75	0.02 – 0.05	0.15 – 0.40	0.40 – 1.25
Southern	1.25 – 3.75	0.02 – 0.05	0.50 – 0.60	1.00 – 1.50
	1.24 – 4.25	0.05 max.	0.40 – 0.90	1.00 – 4.00

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[1] *Iron Age*, December 1, 1921.

	Silicon, per cent.	Sulfur, per cent.	Phosphorus, per cent.	Manganese, per cent.
Charcoal:				
Northern	0.10 – 2.50	0.01 – 0.03	0.15 – 0.28	0.25 – 1.30
Southern	0.10 – 1.75	0.02 – 0.03	0.40 – 0.60	0.20 – 1.25
Cold blast	1.50 – 2.00	0.01 – 0.02	0.35 – 0.45	0.30 – 0.40
Special low phosphorus	0.75 – 1.25	0.03 max.	0.03 max.	0.50 max.
Washed metal	nil	0.01 – 0.04	0.01 – 0.04	nil

A further quotation is given from a paper by Mr. Y. A. Dyer published in *Iron Age*, issue of June 22, 1922:

> ### Mixing Northern and Southern Irons.
>
> By long experience the Northern foundryman has learned that by mixing Southern irons with Northern irons he is able to confine the phosphorus and manganese within certain prescribed limits in his mixtures, thereby producing the ideal chemical and physical analyses for various lines of castings. It is also well known that a blend of Northern and Southern irons gives strong physical characteristics. Therefore, the Southern foundryman may well afford to emulate his Northern brother and use Northern irons with Southern irons in his efforts to raise the standard of his castings.
>
> Special Northern irons are low in phosphorus and high in manganese, and standard Southern irons are high in phosphorus and low in manganese. When the two are mixed in the correct proportions, phosphorus and manganese are controlled to the point necessary to produce a casting of maximum strength and toughness, avoiding the brittleness due to high phosphorus and creating strength and toughness by medium or high manganese content. Manganese offsets "red shortness," due to oxygen which may be retained in the iron, by fluxing it as manganous oxide; also prevents excessive sulfur by fluxing it as manganese sulfide.
>
> ### What Can Be Done in Mixtures.
>
> Note the difference in analysis of special Northern and standard Southern irons:
>
> | | Silicon, per cent. | Sulfur, per cent. | Phosphorus, per cent. | Manganese, per cent. |
> |---|---|---|---|---|
> | Northern | 2.25 – 2.75 | 0.025 – 0.05 | 0.20 – 0.35 | 1.25 – 1.50 |
> | Southern | 2.25 – 2.75 | 0.025 – 0.05 | 0.90 – 1.10 | 0.25 – 0.60 |
>
> By mixing from 30 to 50 per cent of this Northern iron with 70 to 50 per cent of Southern iron, an average range of analyses may be obtained as follows.
>
> | Silicon, per cent. | Sulfur, per cent. | Phosphorus, per cent. | Manganese, per cent. |
> |---|---|---|---|
> | 2.25 – 2.75 | 0.025 – 0.05 | 0.60 – 0.75 | 0.75 – 0.85 |
>
> For regular routine foundry work the 50-50 per cent Northern-Southern iron mixture cannot be surpassed for the following chemical analyses:
>
> | Pig, per cent. | Scrap, per cent. | Castings. | Silicon, per cent. | Sulfur, per cent. | Phosphorus, per cent. | Manganese, per cent. |
> |---|---|---|---|---|---|---|
> | 30 | 70 | Heavy | 1.70 | 0.09 | 0.60 | 0.45 |
> | 40 | 60 | Medium | 1.85 | 0.09 | 0.60 | 0.50 |
> | 60 | 40 | Light | 2.10 | 0.08 | 0.60 | 0.55 |

Cupola charges per ton (2000 lb.) of metal would be as follows to produce castings of above analyses:

	Lb.
Heavy:	
15 per cent Northern iron	300
15 per cent Southern iron	300
70 per cent No. 1 scrap	1400
	2000
Medium:	
20 per cent Northern iron	400
20 per cent Southern iron	400
60 per cent No. 1 scrap	1200
	2000
Light:	
30 per cent Northern iron	600
30 per cent Southern iron	600
40 per cent No. 1 scrap	800
	2000

Of course for less important work more scrap may be used; but for special high-duty castings a larger percentage of Northern iron would be necessary to lower the phosphorus and raise the manganese. Desirable analyses may be worked out from this average mixture of 2.50 per cent silicon for the two pig irons, or even lower silicon if light weight (thin section) scrap be used.

In conclusion, if this course I have suggested is followed, we will secure a satisfactory tabulated statement of the different grades of pig iron and their chemical compositions from the blast furnace men's grading as used in everyday practice. These will no doubt agree in many cases with the corresponding tables of compositions of irons ordered by the foundrymen under the committee's Cast Iron Specifications. The next step will be to agree upon a representative standard set of requirements protecting fairly the interests of both producers and consumers, as an addition to our present specifications. Such specifications or requirements will come into general use and eliminate the necessity of some of the differences that exist today. This would be of considerable service both on home and export orders and in addition, it would make possible a resumption of the pig-iron warrant system in this country, if that were found desirable.

APPENDIX.

NOTE ON A SCHEME FOR THE STUDY OF THE PHYSICS OF CAST IRON.

By Richard Moldenke.[1]

In March, 1895, Mr. William R. Webster contributed a carefully prepared scheme for the study of the physics of cast iron to the American Institute of Mining Engineers at its Florida meeting. This summary of the interrelation of the chemical and physical characteristics of cast iron with the operations of daily foundry practice caused a wide discussion of the then little understood though universally used material. Mr. Webster has requested the author to bring the subject up to date, and while glad to comply, it must be said that with all the knowledge that has been gained in the quarter century that has passed since the subject was brought to the attention of the Institute—and we now are pretty familiar with cast iron in all its aspects—there is practically nothing to change and little to add to the facts as given by Mr. Webster originally,[2] and in the discussions.

The suggested lines for discussion and investigation as they would appear at the present time are as follows:

I. Relation between chemical composition and physical properties, such as fusibility, fluidity, set, contraction, chill, hardness, strength, specific gravity, etc.

II. Influence of variations in foundry practice upon chemical composition and physical properties, as in the following summary:

Mixture Characteristics: Pig and scrap proportions, steel additions, charcoal or coke irons, "direct" blast furnace metal. *Metals' Characteristics:* Clean or with sand, rust, "burnt" scrap, shot, borings, salamanders and heavy section pieces. *Melting Characteristics:* Rational or poor charging and melting practice in cupola or furnace, normal hot iron or oxidized "lifeless" quick-setting metal. Duplexing in electric furnace for better super-heat, deoxidation and desulfurization. *Temperature Characteristics:* Pouring temperature and rate of cooling due to mold surface characteristics, whether green or dry sand, metal molds, use of chills, section of castings, refractory quality of mold, gating of molds. *Molecular Treatment:* Annealing, seasoning, rumbling, repetition, heating and cooling.	Effect on	Grain structure. Internal shrinkage, porosity. Blowholes. Hardness. Strength. Internal stress. Carbon condition. Changes in other contained elements.

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[1] Consulting Engineer, Watchung, N. J.

[2] *Transactions*, Am. Inst. Min. Engrs., Vol. XXV, p. 84 (1895); discussion, Vol. XXV, p. 964 (1895); Vol. XXVI, p. 997 (1896).

The following bad characteristics in castings are sufficiently important to warrant special mention in separate paragraphs:

III. *Shrinkage* and *Segregation:* As specially affected by composition, oxidized metal through bad melting practice, cold metal, irrational gating methods, insufficient feeding opportunity, low ferrostatic pressure.

IV. *Blowholes:* As specially affected by oxidized ("burnt") metal in charges or through bad melting practice, cold iron, low ferrostatic pressure, wet mold surfaces, wet or insufficiently vented cores.

While the scheme for study as outlined in 1895 differs but little from the one above given, the conditions obtaining in foundry practice today are, nevertheless, vastly improved. Buying pig iron by its analysis is the rule everywhere and fracture is seldom an issue. The foundry foreman of today has no difficulty in calculating his mixtures chemically, and the composition of the various types of castings are almost standardized. Melting practice has now been placed upon a scientific basis in the foundry, so that there is little excuse for heavy losses from inferior metal. There still remains, however, a critical study of the principles and practice connected with the rational gating of molds.

A discussion of every point included in the above scheme of study would assume the bulkiness of a book, and hence no attempt will be made in that direction. The summary of a life's work in the production of good castings—necessarily interwoven with the chemical and physical characteristics of cast iron—is as follows:

1. Use the best materials suited to the production of the castings wanted.
2. Employ correct melting, molding and finishing process.
3. Gate the molds correctly, so that the good materials, properly manipulated, may be given the best chance possible to produce good work.

It was through the active work of the American Institute of Mining Engineers in the study of pig iron that the change was brought about from the purchase of pig iron by its fracture to its classification and purchase by its chemical composition. That work was taken up by the Committee on Cast Iron of the American Society for Testing Materials, who brought into general use their specifications governing the grading and purchase of pig iron.

The present condition of the pig iron situation is about the same as the status of steel when the change was made from iron to the use of steel for structural purposes. At that time every engineer desired to have his name on his specifications. Since then the whole matter has been cleared up and we now have standard specifications which are in general use. These results were brought about by giving the producers and the consumers equal representation and vote on the committees preparing these specifications. This same plan can be followed to great advantage in pig iron. Under the present conditions the requirements of the founders sent to the blast furnace men are not uniform even when they are making the same grade and weight of castings and many requirements are "hair splitting," which entails unnecessary trouble to all parties. The natural solution of the present condition is to collect the requirements under which pig iron has been sold for each of the grades of castings, manufactured malleable iron, acid open-hearth steel, basic open-hearth steel, etc., the work to be done by a committee having an equal representation of blast furnace men, whom we term the producers, and the consumers who manufacture the finished product. The requirements to insure reliability of their finished product have already been put into use and need not be further considered.

If this course is followed out, then it would enable any blast furnace in the country to produce a much larger output on a given grade of pig iron than ever before, as the number of grades would be reduced and the hair-splitting requirements removed. In dull times this would enable the furnaces to stock up considerable of each grade of iron with much more certainty than under the present conditions.

[This paper was discussed jointly with the Report of Committee A-3 on Cast Iron. For this joint discussion, see Part I of the *Proceedings*, page 137.—ED.]

A METHOD FOR DETERMINING THE SPELTER COATING ON IRON AND STEEL SHEETS BY MEASURING THE RISE IN TEMPERATURE OF THE ACID EMPLOYED.

By D. M. Strickland.[1]

This paper describes a new method for the determination of spelter coating on iron and steel sheets, the value of the method lying in the fact that coating weights can be determined without the use of the analytical balance. A galvanized specimen is immersed in a measured amount of acid, the maximum temperature rise being recorded. Each one-tenth degree rise in temperature is equivalent to a definite weight of zinc.

Apparatus.

In Fig. 1 is shown the equipment needed, consisting of a ground-stoppered bottle containing concentrated hydrochloric acid, a graduated volumetric flask used to measure the acid, a testing jar, and a thermometer. Providing the sides and bottom are not too thick, almost any container similar to the one illustrated would be satisfactory. In fact, the author has obtained very accurate results when using an ordinary glass tumbler. An alloy coated sheet-iron container was also used, but, although the results were satisfactory, the service life of a metal container is limited, whereas glass can be used indefinitely. The size of the jar should be approximately 2½ in. in diameter. An elliptical shaped container is very advantageous as will be pointed out hereafter. The thermometer is the only precision instrument needed, being in fact, the only item of apparatus which is in any way costly. A suitable thermometer should be graduated in tenths of a degree Centigrade with a range of, perhaps, fifty degrees.

Manipulation.

A measured amount of concentrated hydrochloric acid is poured into the testing jar. The base metal may be slightly attacked without danger to accuracy, consequently, it is not necessary to add antimony trichloride to the acid. The volume of the acid chosen regulates the conversion factor, that is, the value in grams for each

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[1] Research Engineer, The American Rolling Mill Co., Middletown, O.

0.1°C. rise in temperature. The smaller the volume of acid used the greater will be the rise in temperature for each gram of zinc dissolved. Several series of experiments were run using volumes of acid which varied in amounts from 100 to 300 cc. and, although the conversion factor was different for each volume used, nevertheless the coating weight was accurately determined regardless of the acid volume employed. It must be pointed out, however, that when an exceptionally high coating weight is determined (3 or 4 oz. per sq. ft.) the acid volume for the usual size of specimen should never be less than 300 cc. The shape of the testing jar regulates to some extent the volume of acid needed. It is obvious that sufficient acid must be present to insure complete immersion of the sample. A smaller volume of acid can be used for the same height test piece if the tumbler is elliptical in shape rather than circular. Experiments were also conducted using a container rectangular in shape. Very close checks were obtained using all the various shaped containers mentioned. The height of the container is not important except that it must

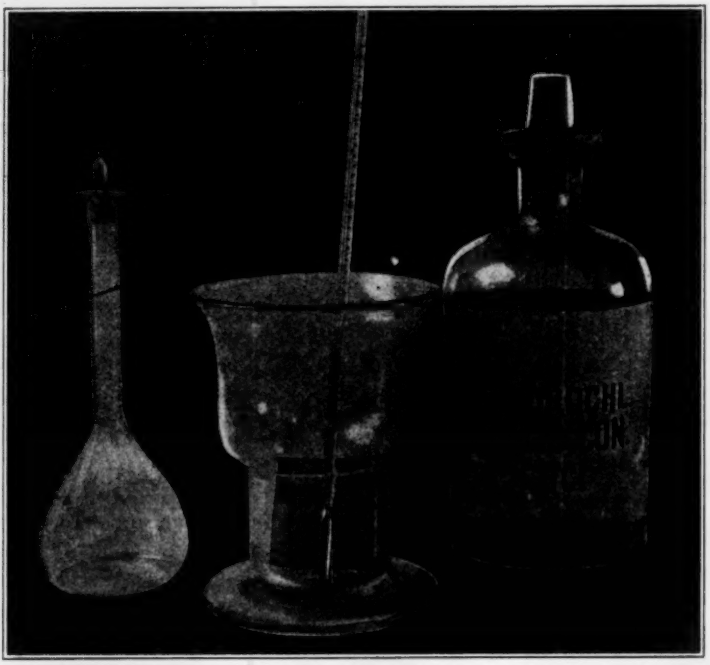

FIG. 1.—Apparatus for Temperature Rise Method of Coating Determination.

be at least of such height that no acid bubbles out at the moment the evolved gas causes the liquid to rise. The flared top on the glass shown in Fig. 1 is advantageous since it serves to keep the liquid from overflowing when it rises.

After the acid is poured into the container, it is stirred thoroughly to insure an equalized temperature. The thermometer is immersed in the liquid, and when the temperature is constant, the reading is recorded. The galvanized specimen is immersed in the acid (the spelter coating dissolving very rapidly), the heat evolved being absorbed by the acid. The action is so rapid that the spelter is dissolved and the maximum temperature reached in about thirty or forty seconds; consequently, radiation does not interfere with accuracy. The maximum temperature is then recorded. The rise in temperature multiplied by an experimental conversion factor gives the grams of zinc originally carried by the test piece. The entire time required for a determination is very short, the entire operation being finished in three minutes or less.

To standardize the equipment, five or six galvanized specimens (any convenient gage or size) are weighed, the rise in temperature determined using the same container, thermometer and volume of acid. The samples are washed, dried and reweighed, and the difference in weight noted. The weight in grams is divided by the corresponding rise in temperature expressed in degrees. When carefully determined, the five or six quotients will agree very closely and an average gives a conversion factor which is thoroughly reliable with the equipment used and for the volume of acid employed.

DISCUSSION OF SAMPLES.

The samples used for a coating weight determination must be clean. For this reason it is customary to wash them off with gasoline. The size of the sample is immaterial except that it must not be too large for the testing jar. Since the coating weight is customarily reported in ounces per square foot, a $2\frac{1}{4}$ by $2\frac{1}{4}$-in. test piece has been found convenient as the weight of zinc in grams is then numerically equal to the ounces per square foot desired. When only irregularly shaped pieces are available, it is advantageous to use a planimeter for accurately measuring surface areas. The sample is placed on a sheet of plain white paper and a pencil run around the edge. The area of this figure, which is the area of the test piece, may then be read directly by means of the planimeter. The area obtained may be compared to the area of a $2\frac{1}{4}$ by $2\frac{1}{4}$-in. specimen (5.08 sq. in.) and the ounces per square foot calculated by proportion.

EXPERIMENTAL DATA.

Table I contains experimental data which shows the accuracy of the temperature rise method of coating determination. The determinations obtained by the temperature rise method are compared with results obtained by the hydrochloric acid method. These comparative figures are all the more interesting because they are absolute comparisons. Each sample was weighed before the coating weight was determined by the temperature rise method. When the temperature was recorded, the sample was dried and re-weighed, the difference in weight giving the coating weight by the hydrochloric acid method. The same sample was thus used for both determinations.

TABLE I.—EXPERIMENTAL DATA ON TEMPERATURE RISE METHOD OF COATING DETERMINATION.

Material.	Size, in.	Gage No.	Volume of Acid Used, cubic centimeters	Conversion Factor for Volume Used.	Temperature Rise, deg., Cent.	Grams of Zinc by Temperature Method.	Grams of Zinc by HCl[1] Method.	Difference.
Galvanized iron	2 by 2	14	100	0.168	11.0	1.85	1.85	0.00
Galvanized iron	2 by 2	14	"	"	12.1	2.03	2.02	0.01
Galvanized iron	2 by 2	10	"	"	12.0	2.02	1.98	0.04
Galvanized iron	2 by 2	16	"	"	8.4	1.41	1.42	0.01
Galvanized iron	$2\frac{1}{4}$ by $2\frac{1}{4}$	28	"	"	5.2	0.87	0.88	0.01
5 nails, electro galvanized	......	..	120	0.191	3.0	0.57	0.60	0.03
10 nails, electro galvanized	......	..	"	"	5.5	1.05	1.10	0.05
5 nails, hot-dip galvanized	......	..	"	"	13.0	2.48	2.43	0.05
10 nails, hot-dip galvanized	......	..	"	"	24.0	4.58	4.62	0.04
Metallic zinc sawings	......	..	"	"	3.5	0.67	0.70	0.03
Metallic zinc sheet	......	..	"	"	9.0	1.72	1.70	0.02
Metallic zinc sawings	......	..	"	"	9.0	1.72	1.70	0.02
Metallic zinc sheet	......	..	"	"	25.0	4.77	4.71	0.06
Galvanized iron	2 by 3	26	"	"	10.5	2.01	2.02	0.02
Galvanized steel	2 by 3	26	"	"	9.5	1.81	1.82	0.01
Galvanized steel	2 by 3	26	"	"	8.5	1.62	1.68	0.06
Galvanized steel	2 by 2	16	"	"	8.0	1.53	1.52	0.01
Galvanized steel	2 by 2	16	"	"	7.0	1.34	1.34	0.00
Galvanized iron	2 by 2	16	"	"	11.0	2.10	2.06	0.04
Galvanized iron	2 by 2	16	"	"	12.0	2.29	2.27	0.02
Galvanized iron	irregular	20	"	"	8.3	1.59	1.61	0.02
Galvanized iron	$2\frac{1}{4}$ by $2\frac{1}{4}$	12	"	"	15.0	2.87	2.88	0.01
Galvanized steel	$2\frac{1}{4}$ by $2\frac{1}{4}$	16	200	0.305	4.1	1.25	1.28	0.03
Galvanized steel	$2\frac{1}{4}$ by $2\frac{1}{4}$	24	"	"	3.9	1.19	1.23	0.04
Galvanized steel	$2\frac{1}{4}$ by $2\frac{1}{4}$	24	"	"	4.1	1.25	1.26	0.01
Galvanized steel	$2\frac{1}{4}$ by $2\frac{1}{4}$	24	"	"	4.2	1.28	1.29	0.01
Galvanized steel	2 by 2	24	"	"	6.7	2.04	2.04	0.00
Galvanized iron	2 by 2	20	"	"	7.3	2.23	2.23	0.00
Galvanized iron	2 by 2	20	"	"	7.2	2.20	2.20	0.00
6 rivets	......	..	"	"	1.3	0.40	0.41	0.01
Galvanized iron	$2\frac{1}{4}$ by $2\frac{1}{4}$	10	300	0.425	10.1	4.29	4.25	0.04
Galvanized iron	$2\frac{1}{4}$ by $2\frac{1}{4}$	10	"	"	12.3	5.22	5.30	0.08

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[1] J. A. Aupperle, "The Determination of Spelter Coating on Sheets and Wires." *Proceedings*, Am. Soc. Test. Mats., Vol. XV, Part II, p. 120 (1915).

APPLICATION OF THE METHOD.

The application of the method is not limited to sheet metal alone, but can be used equally as well for rivets, nails, wire or anything in fact which carries a coating weight and on which the surface area can be determined.

The temperature rise method of coating determination is very serviceable for field tests. The equipment needed can easily be packed in a small box and carried from place to place. The testing jar and the thermometer take the place of the analytical balance. To test a sample in the field it is only necessary to clip a piece from the sheet to be tested and drop it in the acid, after which the temperature rise is recorded.

The cost of a portable outfit would be nominal, being less than $15. The only equipment needed would be a bottle of concentrated hydrochloric acid, an accurate 300-cc. graduate, a thermometer, a suitable testing jar or tumbler, a pair of tinner's snips, and a ruler. Such equipment may be compactly fitted into a small box. A planimeter can also be added if desired. The manipulation is simple; any user of galvanized material can accurately determine a galvanized coating weight.

PRELIMINARY NOTES ON CORROSION.

By Wilder D. Bancroft.[1]

We may divide metals and alloys into two classes; those which are corroded by the medium and those which are not. All the ordinary metals, such as aluminum, zinc, iron, copper, etc., come in the first class, while gold under ordinary conditions seems to belong in the second class. From an academic point of view, it is open to question whether any metals belong in the second class. Most people would put platinum there; but it is now known that platinum black is unquestionably oxidized on the surface, which makes it probable that massive platinum has an oxide film over it.

However that may be, the class that interests us is the first one, in which the metals are corroded by the medium. While it is probable that we have all gradations inside this class and while it is possible that we cannot draw a sharp dividing line, we can distinguish the extreme cases without difficulty. In the one case the corrosion continues until the metal is destroyed and in the other the attack comes practically to a stand-still. Iron and nickel are two striking illustrations of this. Although iron and nickel are close together in the Periodic Table, we electroplate iron with nickel in order to preserve it.

If a metallic surface is corroded by the medium, the attack must continue so long as the unchanged surface is exposed to the unchanged medium. A cessation of the attack under otherwise changed conditions can occur only when the unchanged medium does not come in contact with the unchanged metallic surface—in other words when the metallic surface becomes coated with a film which prevents the corroding medium from coming in contact with the metallic surface. In a way this is a truism. Everybody knows it except the people who study corrosion. We paint or varnish metals to protect them. We know that aluminum and nickel owe their relative stability to the formation of an oxide film. Everybody knows that a copper roof turns green fairly rapidly and that the coating of basic carbonate retards the action of the weather on the underlying copper. Parkerized iron owes its resistance to corrosion to the presence of a film of oil and phosphate. Coating iron suitably with ferro-ferric oxide decreases the corrosion, while an unsuitable coating with the same compound accelerates the corrosion. Lead and lead peroxide in sulfuric acid form a storage battery; but the positive plate consists of lead and lead peroxide without being a short-circuited cell, because the lead peroxide coats the lead and prevents the sulfuric acid from coming in contact with it. The whole problem of retarded corrosion is therefore essentially a question of film formation. This has been recognized explicitly by Buck, Richardson, and others; but it is not generally accepted as yet and very little has been done along the line of determining the theoretical condition necessary for the formation of a protecting film. Great stress is still laid on electromotive force measurements, though these are practically valueless. The measurement of the electromotive force shows which of two metals has the greater tendency to start corroding, a thing which is only of academic interest; it shows nothing as to the important question whether the metal will keep on corroding. Electromotive force measurements would tell us nothing about the marked difference between iron and nickel unless the measurements were made so badly that they were not measurements of the true electromotive force. We find a striking illustration of the futility of electromotive force measurements in the case of the copper-tin alloys. The electromotive forces of all the alloys lie between those of tin and of copper and one would therefore expect the corrodibility to decrease as one went through the series from tin to copper. As a matter of fact, Curry[1] found that the electrochemical corrosion is relatively slight in most solutions for the bronzes containing 40 to 75 per cent of copper and is much higher for alloys richer in copper or in tin. The reason for this apparent passivity was found to be the formation of a surface film of stannic oxide; but we do not know why this particular type of film is formed in these particular alloys.

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A good many people do not believe that there is an oxide film on the surface of passive iron; very few people believe that there is an oxide film on the surface of chromium or of ferrochrome; and we are still more vague in regard to ferrosilicon. An independent test for the existence of such a film would be very desirable. I think that a test can be developed which will be applicable in most cases, though perhaps not in all. If we make lead an anode in sulfuric acid, it becomes coated with lead sulfate which is then oxidized to lead peroxide, this latter forming a film which protects the lead beneath pretty well from further electrolytic corrosion. If we reverse the current, the lead peroxide is reduced to lead sulfate or to spongy lead as the case may be.

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[1] *Journal of Physical Chemistry*, Vol. X, p. 474 (1906).

By successive reversals of the current—in other words, by successive oxidation and reduction—it is possible to corrode the plate to any extent one pleases. This is the Planté method of forming storage battery plates. It is sure but it is slow. If we pass an alternating current through lead electrodes in sulfuric acid, and make the current density high enough, the lead corrodes completely to lead sulfate. This might be applied in other cases where there is a film; but the objection might be made to it that, with so high a current density, one does not know the temperature at the electrode surface sufficiently accurately. It would be worth while to try the effect of superposing an alternating current on a direct current with lead electrodes in sulfuric acid. While this might not work on account of the insolubility of lead sulfate, we know that it causes the electrolytic corrosion of platinum.[1] It seems probable that an alternating current superimposed on a direct current would cause passive iron to corrode in concentrated nitric acid, especially since we know that an alternating current alone[2] will cause iron to corrode in nitric acid (sp. gr. 1.40). No experiments of this sort seem to have been made with chromium; but we know that chromium becomes passive when made anode in hydriodic acid; but dissolves when no current flows, because of the activation due to the hydrogen set free at the surface of the metal.[3] In the case of ferrosilicon, the method might fail, because a film of silica, if formed, would not necessarily be reduced.

After the existence of surface films has been shown in the doubtful cases, it is very desirable that suitable methods for the microscopic study of these films should be developed. It is quite likely that an entirely new technique may be necessary, in which case this work will have to be done by Professor Chamot. The next step will be to study the properties of these films more carefully than has hitherto been done. If we can get a protecting film of stannic oxide by corroding certain bronzes, is it not possible to prepare such a film in such a way that we could apply it to other metals? This is the more probable because of what we know has been done with parkerized iron. Even if this could be done, it would not be absolutely satisfactory, because it would act like a varnish and would not protect if cracked. What we really want is a self-healing film. It might be possible to add something to pure tin which would cause it to corrode to stannic oxide with the properties of the stannic oxide obtained by electrolytic corrosion of the copper-tin bronzes containing 40 to 75 per cent of copper. The reverse state of things is possible because addition of potassium chlorate to sulfuric acid causes the formation of a porous lead peroxide instead of a protecting film. This makes the rapid formation of peroxide plates a possibility; but it was not a success commercially because it was not possible to remove the chlorate completely and so the plates continued to corrode. Whenever a metal surface is subject to erosion, a self-healing film is absolutely necessary.

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[1] Margules, *Wied. Ann.*, Vol. 65, p. 629; Vol. 66, p. 540 (1898). Ruer, *Zeit. phys. Chem.*, Vol. 44, p. 81 (1903); *Zeit. Elektrochemie*, Vol. XI, p. 11, 661 (1905). Haber, *Zeit. anorg. Chem.*, Vol. 51, p. 365 (1906).

[2] Ruer, *Zeit. Elektrochemie*, Vol. 9, p. 239 (1903).

[3] Bennett and Burnham, *Journal of Physical Chemistry*, Vol. XXI, p. 147 (1917).

We must determine just what sort of a film is formed when copper-bearing steels are exposed to atmospheric corrosion and we should then show that this same sort of film is not formed or does not protect when these steels are immersed in liquids.

A rapid method for studying corrosion is very desirable andm ust be developed. It seems probable that such a test will be an electrochemical one; but there is no convincing proof of this. We know that there is an approximate parallelism between chemical and electrochemical corrosion under certain conditions; but we do not know the limitations nor the best way to carry out the electrochemical tests. Let us consider the chemical corrosion of an alloy in a concentrated sodium-chloride solution exposed to the air. Will the chemical corrosion be the same as the electrochemical corrosion? At first sight the question seems absurd because the chemical corrosion is obviously due to oxygen while electrolysis of a sodium chloride solution sets free chlorine; and everybody knows that the action of chlorine on alloys is, or may be, quite different from that of oxygen. On the other hand Curry[1] found that the chemical corrosion of the bronzes in sodium chloride solutions was quite different from that in sodium persulfate solutions and was unexpectedly like the electrochemical corrosion in chloride solutions, while the persulfate solutions behaved like electrolyzed sulfate solutions. The difficulty disappears if we do not consider the oxygen of the air as acting directly upon the alloy. If we consider that we have a cell with a metal anode and an oxygen cathode, the results of the chemical corrosion will be identical with those of the electrochemical corrosion except in so far as variation of current density affects the results. Experiments should be made with carefully selected alloys to determine chemical corrosion in different salt solutions of different concentrations and these experiments should be paralleled by electrochemical experiments with the same salt solutions at different current densities so as to determine at what limiting current densities, if any, chemical and electrochemical corrosion are identical or nearly so.

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[1] *Loc. cit.*

Of course the results of a rapid electrochemical test will not necessarily be applicable directly to a case of atmospheric corrosion. The behavior of the copper-bearing steels shows that. If we once get one part of the problem worked out in good shape, it is practically certain that it will be a simple matter to modify either the experiments or the conclusions so that we can discuss atmospheric corrosion satisfactorily. The difficulty at present is not that we cannot explain everything; it is that we have nothing definite of which we are absolutely certain.

It does not seem worth while to take up at present the artistic production of films or patines; but it is worth noting that the laboratory patines are less satisfactory than those produced by slow action because they are too transparent, in other words, too nearly invisible.

DISCUSSION.

Mr. Speller.

MR. F. N. SPELLER (*presented in written form*).—The classification of metals according to whether or not a protecting film is formed under certain conditions or in a certain medium, suggests the question: "What changes are necessary in a medium so that a protective film will be formed on a metal that would be otherwise corroded away in that medium?"

Mr. Bancroft has pointed out how a small change in composition of the metal in some cases will greatly influence its resistance in certain mediums, as in the case of the addition of a small amount of copper to iron under atmospheric conditions. Unfortunately, changes in composition so far have not given such favorable results on the corrosion of iron under water, so we have been attacking the problem from the other side by changing the conditions to protect the metal.

In studying corrosion of iron there has been found to be such a wide difference between under-water and atmospheric corrosion that this classification seems logical and convenient depending as it does on whether the free oxygen necessary for continuous corrosion is limited or not. In the former case (under-water), the corrosion depends on the amount of oxygen available; in the latter where an unlimited amount of oxygen is present, corrosion depends on the rate of solution of iron in water. This may explain why we find that changes in composition of steel have, as a rule, very little influence under water, whereas some elements, notably copper, when present in comparatively small amounts have a very marked influence in retarding corrosion in atmosphere.

The writer has discussed before the practical possibilities of "self-healing" films in retarding corrosion of iron under water[1] and has already done considerable work on the formation of such films or scales in water systems. In the case of metals such as iron or zinc under water (especially where heated) such films usually form by reaction between the products of corrosion and the lime and silica present in water. The wide variations in corrosion of water pipes in different parts of the country may be accounted for by the formation or lack of such films.

The removal of 7 or 8 p.p.m. of free oxygen from water forms the basis of what promises to be a new industrial development in appa-

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[1] *Journal*, Franklin Institute, Vol. 193–4, April, 1922, pp. 519–520.

Mr. Speller. ratus for control of internal corrosion; in this case also, when the corroding medium is soft domestic water with no power to form a natural protective film, by removing this small amount of oxygen a hydrogen film quickly forms and protects the metals from further damage. Where free acid is present, in the absence of oxygen the iron will be still subject to attack but at a retarded rate.

The author refers to the desirability of a rapid method for studying corrosion. All who have studied the corrosion problem in detail must have felt this need. In experiments on corrosion under water, the writer has found that the oxygen consumed in water passing through a fixed length of iron tubing affords a reliable means of testing quickly the influence of many factors on corrosion. We have used this method in studying the influence of temperature, velocity of flow, alkalinity and the retarding influence of films or scales. Perhaps this system of measurement will be found useful in a wider study of the corrosion problem.

Mr. Rawdon. MR. H. S. RAWDON (*presented in written form*).—The suggestions given by the author are so fundamental in their nature and of so wide applicability that, without doubt, they must be considered as the most helpful which have been offered on this subject. It appears to the writer, however, that these suggestions apply in a practical way most readily to the "pure" metals and to the simpler alloys, and that there are many other contributing factors which determine the "corrodibility" of metallic materials, in general, which must be given full consideration in the study of this problem. The production of a protective self-renewing surface film is, of course, in the last analysis, the ideal solution of the problem and the writer does not wish to imply anything to the contrary. A full realization of the many contributing factors in corrosion, both in the nature of the metallic materials used, as well as in the external circumstances, which comprise the service conditions, is necessary before any rational attempt can be made to carry out such suggestions.

The writer feels that the author's statement that "everybody knows it except the people who study corrosion" is not borne out by facts. One important instance to the contrary which may be cited by way of illustration, is the common metallurgical practice of adding small amounts of tin in mixing up brasses which, in service, will be subjected to sea-water corrosion. The addition of this element, in amounts as low as 1 per cent, to brass of the 60 : 40 and the 70 : 30 type has been found to increase the resistance to corrosion of such materials enormously. Careful study of the alloys, the work of C. H. Desch being foremost in this field, has shown that the protection is

Mr. Rawdon.

largely mechanical in nature and results from the formation of a tough film of a basic compound of tin which adheres firmly to the surface, thus preventing to a large extent further attack of the metal. By the use of such alloys, the life of steam-condenser tubes is very greatly lengthened, particularly on sea-going vessels. The extensive studies of the Corrosion Committee of the British Institute of Metals have shown, however, that the answer to the problem of condenser-tube corrosion is not reached so easily. Due consideration must be had for the various factors contributory to corrosion of which may be mentioned the surface condition of condenser tubes, crystallin structure of the material, surface accumulation of corrosion products, mechanical effects resulting from variations in the speed of the water circulating through such tubes, temperature of cooling water, the presence of deleterious substances in the water, for example, iron compounds, which may under certain conditions give rise to substances which are highly corrosive in nature.

If the corrosion of a metal were uniform, the problem would be greatly simplified. In such a case allowance could be made for the gradual but uniform loss which the material suffered. However, it is the localized attack, often in the form of pitting, which is the source of most of the trouble and loss which corrosion entails. It is very disconcerting, to say the least, to have a copper roof become perforated at numerous, though isolated, spots while the roof as a whole is still in excellent condition or to have a copper brine coil such as is used for the cooling of milk after pasteurization and in other processes develop a few holes which permit the mingling of the brine with the milk or cream, while the tube as a whole otherwise is as sound as it ever was.

The use of a "non-corrodible" material does not necessarily mean freedom from corrosion, as is illustrated by the case of the sea-going yacht, the "Sea-Call," which though sheathed with monel metal, one of the most resistant of all alloys used in naval construction, never made a trip worth while. The accelerated corrosion resulting from the exposure to sea water of the two dissimilar materials, steel and monel metal, in intimate contact with each other is a most striking example of the necessity for a consideration of some of the contributory underlying factors in corrosion. It is difficult to see how, in this particular case, corrosion could have been eliminated by the "spontaneous" formation of a protective surface film on the steel. Very similar cases are those in which the attack is accelerated because of the action of an applied electromotive force, resulting from "stray currents."

The physical character of a metal, for example, a casting, has a

Mr. Rawdon. great deal to do in determining the life when exposed to corroding service conditions. In the paper and pulp industry, bronze of approximately 90 per cent copper, is used extensively for parts exposed to the sulfite liquors and is probably as suitable for this purpose as any other alloy, if not more so, all circumstances such as the price being considered. The life of some bronze castings under such conditions may be as long as five years and more, while similar castings may give out before a year has elapsed. In cases of this kind, examined by the writer, it appeared that the character of the casting was the determining factor; in the second case, porosity of the metal permitted the access of the corroding liquid into the interior. The corrosion products which were consequently retained in the internal cavities in close contact with the metal accelerated the further attack of the bronze by a process similar to "dezincification" in brass so that the casting became permeated throughout by a net-work of corrosion films and lost its strength and usefulness in a relatively short time. A somewhat similar case arises in the corrosion of anodes, for example, nickel, in the electro-plating process. A metal which corrodes readily and uniformly is desired for this purpose. Instances have been noted, however, in which the corrosive attack of the anodes was very irregular and relatively large particles of metallic nickel became detached and added to the amount of waste in the sludge at the bottom of the tank. The character of the casting was responsible for the inferior corroding properties of the anode. An intercrystallin constituent, which was more readily dissolved than the neighboring metal, was found to be present. By the solution of this constituent the grains of nickel were allowed to fall out of place, often before more than one half of the metal of the grain had been utilized.

Variations in the physical character of an alloy may arise from other reasons, one of the most important being the amount and uniformity of the cold working received. Thus it may happen that a metal or alloy, although chemically homogeneous throughout, is in a very heterogeneous condition as a result of cold working and shows in its increased tendency toward corrosion the effect of this physically heterogeneous state. Numerous other illustrations might be given, if more were required, to emphasize the necessity for understanding thoroughly the conditions which exist within any metal in the study of its behavior under corroding conditions.

Changes in the conditions external to the metal are likewise of great importance in determining the corrodibility of any material. It is well recognized that a metal which is very resistant to corrosion under one set of conditions may deteriorate rapidly when the conditions are changed. As an illustration, the difference in the behavior of copper-bearing steel under atmospheric corrosion in an acid atmosphere and when totally immersed in mine water as determined by Committee A-5, of this Society, may be mentioned. It is usually conceded by investigators of corrosion that the relative behavior of steels in an immersion test is not necessarily any indication of the behavior of the same materials under atmospheric conditions. **Mr. Rawdon.**

The effect of different climatic conditions must also be considered. Some alloys, for example, certain mixtures used as die castings, appear to be entirely suitable for use in this climate. In tropical countries however, they often deteriorate very rapidly by internal oxidation, change their shape and dimensions, and prove entirely useless. Even aluminum, one of the most resistant of the metals to atmospheric agencies behaves quite differently when used in a tropical climate and often acquires a foul taste and odor as a result of the surface attack.

As has already been stated, the writer believes that the suggestions offered by the author may be considered the ideal toward which metallurgists should strive in their endeavor to solve the corrosion problem. We should not, however, lose sight of the conditions near at hand which are so intimately related to corrosion, a knowledge of which will aid us immeasurably in our endeavor to reach the goal.

Mr. Calcott. MR. W. S. CALCOTT.—Our experience along corrosion testing lines has been from an almost radically different viewpoint from that of most of the speakers. Our problem has been primarily to select material which can be used as a container for certain liquids, and has dealt almost entirely with what we call a solvent type of corrosion. In connection with our tests, we have been led to certain conclusions as regards the mechanism of the action. We tried to reduce our results to some order, but found that we could derive no equation that could follow the rate of the reaction in general. In fact, the results were rather chaotic until we tried the hypothesis of treating the corrosion as two consecutive reactions: the first, the formation of some product at the surface of the metal, and the second, the removal of that product. A good illustration would be the action of acetic acid on aluminum. Beginning with pure water, we have unquestionably a protective coat of aluminum oxide or hydroxide on the surface of the aluminum. We were able to deduce an equation from these considerations which would follow the action of acetic acid on aluminum from zero to 99 per cent and then break down, presumably due to the non-formation of the protective coat on account of the absence of water. That same equation, however, would fail when applied to another material.

Mr. Calcott.

We finally came to the conclusion that a protective film might or might not form in any case, in accordance with the relative solubility and rate of formation. For instance, with dilute acetic acid and aluminum, the rate of formation is great compared with the rate of solution; therefore the limiting factor was the rate of solution of aluminum hydroxide. In the case of copper and hydrochloric acid, the conditions are quite the reverse, as the acid does not appear to attack the metal in the absence of air. In this case, the limiting factor was, therefore, the rate of oxidation rather than the rate of solution. Considering the problem from this point of view, we were able to develop equations that would enable us to answer our main problem—the application of laboratory results to plant conditions—with a fair amount of success, as well as to explain certain apparent anomalies that had been observed. Under the latter class, the most conspicuous example was the difference in the behavior of lead toward sulfuric acid, in the laboratory and in the plant. The frequent failures in the plant were simply due to the increased rate of solution of the protective coating (in this case lead sulfate), on account of the greater velocity of the plant solutions. This latter phenomenon was found to be of fairly frequent occurrence: that is, a protective coat under a certain set of conditions would fail entirely under a different set of conditions, even though the corrosive medium was the same. In other words, a general protective film could not be said to exist, although we found it was, in general, possible to predict whether a given film would be protective under a given set of conditions or not, within the rather specialized field covered by our investigations.

Mr. Walker.

MR. W. H. WALKER.—This is a characteristic Bancroftian contribution, in that it is replete with valuable suggestions but is not without its facetious remarks usually of doubtful validity. Mr. Rawdon has already called attention to one of these, in which Mr. Bancroft states that "everybody knows it except those who study corrosion." Had Mr. Bancroft sat in with Committee A-5 during the last ten years, he would not have made this statement. If we must have an epigram, I would paraphrase this to read, "Everybody knows it except those who don't know what is known by those who study corrosion." A second statement which is a surprise to me and which I think is erroneous is this one: "Great stress is still laid on electromotive force measurements though these are practically valueless." Committee A-5 studied this matter years ago and came to the conclusion that electromotive force measurements were valueless, and I do not believe it is true that anyone places great reliance upon them at this time. Mr. Bancroft's remark about passivity is certainly true, and it is remarkable that **Mr. Walker.** so much work could have been done upon a subject, as that which has been expended upon the passivity of iron, and yet the fundamental factors controlling it continue to evade us; we do not yet know with complete accuracy what passivity of iron is, or what its real and essential factors are. It is a splendid field for investigation, and if some of our young research men would be satisfied to take a small area of it or any of these very interesting suggestions that Mr. Bancroft makes, and cultivate this area intensively, instead of, as most of us attempt to do, take a large area on which we can be but superficial, very great progress, I am sure, would be made. The suggestion that a self-healing film is a desirable thing is unquestionably true. It is rather the irony of fate that our three most common methods for protecting iron are all of such a character that when an abrasion in the film does occur, the mere presence of that abrasion accelerates the corrosion. Take, for example, the magnetic oxide film, that is, the old Bower-Barf process, which is still used on many articles; or tin, as found on "tin plate." Whenever we get an abrasion in either of these films, the very fact of the presence of ferric oxide or the tin accelerates the corrosion of the iron next to it. This is true also in protective coatings of zinc. Although the zinc protects the iron immediately next to it, when an abrasion occurs, the presence of the iron accelerates the corrosion of the zinc so that in time the zinc wears away, continually corrodes, and in time becomes so far distant from the surface of the abrasion that the iron itself commences to corrode. That is seen in the barbs of a barbed wire fence. If you have ever studied this matter, you will find that a barbed wire fence always commences to corrode at the barbs. Where the wire is cut to make the barb, we have a surface of iron which is protected at first because of the zinc which surrounds it, but the protection of the iron is at the expense of the zinc, and the presence of the iron accelerates the rapidity with which the zinc will corrode. In time the zinc wears away to such an extent that the iron is no longer protected, and it corrodes. An adequate explanation of why copper in steel or iron makes it so much less corrosive in the atmosphere, is still wanting. Of course one of the factors which influences corrosion in the atmosphere as compared with corrosion of the same metal in water, is the drying down effect—the skin effect—which is produced when the rust formed while wet is rendered dense and adherent when the article dries.

As I said originally, this paper surely is very welcome on account of the suggestions it contains, and although some of them are pretty far-reaching and difficult to attain, the next step to take—the only

Mr. Walker. step we can take is the next one—is one which follows along these suggestions, and we will doubtless in time reach the ideal which Mr. Bancroft has so well presented.

Mr. Aupperle. MR. J. A. AUPPERLE.—Mr. Bancroft has given us some very good information on film formation. The problem, however, seems to be how to produce such protective films under water conditions. Committee A-5 has studied the film formation on iron and steel, and if you will consult their reports you will find that reference is made to the numerical grades dependent on the texture and also on the color of the rust. The finer grained and darker colored rust exists on those sheets which have resisted the action of the atmosphere better than other grades of sheets. An entirely different film is formed under water conditions or where water instead of air predominates. The results of the action of water on ferrous metals can not be compared with the results obtained when these same metals are exposed to conditions where air instead of water predominates.

The Report of Committee A-5 [1] shows this difference in film formation very clearly. The bessemer copper-bearing sheets "I" received the highest numerical grade based on both texture and color of rust when these sheets were subjected to atmospheric influences. Portions of the very same sheets, however, when subjected to the action of mine water were the first to fail. In other words, the protective film formed under atmospheric conditions was not formed where water instead of air predominated.

I have here (illustrates with the use of three bottles) a laboratory experiment such as has been suggested by Mr. Bancroft. He, however, suggests making the test in the presence of air. In these tests the air was excluded and the bottles were corked for ten months. In this bottle is about a square inch of pure iron in a solution of salt water containing 3 per cent of common salt. According to the electrochemical theory of corrosion, we would expect to find the red hydroxide of rust in the bottle. However, we find the black ferrous ferric oxide. If this oxide is filtered off and dried it will be found to be magnetic. The same thing will be found on the more rust resisting sheets which have been exposed to the atmosphere. Those which have lasted the best will be found to have the highest percentage of magnetic oxide of iron. A test can be made by bending a sheet back and forth, loosening the oxide, and then using an ordinary magnet; it will be found that these dark oxides will be attracted much more by the magnet than the oxides produced on the lighter colored sheets.

In this other bottle I have about a square inch of copper. The

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[1] *Proceedings*, Am. Soc. Test. Mats., Vol. 21, p. 103 (1921).

Mr. Aupperle. copper has corroded to a certain extent and has formed more hydroxide than the iron has formed iron hydroxide. In this other bottle I have a square inch of iron and a square inch of copper in contact with each other. For some reason or other, this has run true to form and has given us the red hydroxide of iron but in a much larger volume than will be found in the bottle containing the iron alone. Mr. Bancroft has said that a copper roof forms basic carbonate and basic hydroxide of copper as a protective film; the problem is to make such a film protective under water as well as atmospheric conditions.

In this test it does not seem that the hydroxide has protected the copper, as it has loosened from the metal and gone to the bottom of the bottle. In the case of pure iron we seem to have what Mr. Bancroft calls a chemical action. In the case of the iron plus copper in the same 3-per-cent salt solution, we seem to have an electrochemical action.

We now have stainless steel, an alloy containing 10 to 20 per cent of chromium. These steels are supposed to be very resistant to corrosion, and they are. If, however, you use a 3-per-cent acetic acid solution, the stainless steel will resist the action of this acid in the cold to a remarkable extent, but heat the solution to boiling, and it will be found that stainless steel dissolves about six times as fast as the pure iron.

Mr. Aston. MR. JAMES ASTON (*presented in written form*).—Mr. Bancroft's paper points out many of the salient features of the corrosion problem, particularly as related to the mechanism of corrosion. Despite allusions to the contrary, many who have followed the problem have realized the significance of the fundamentals. Any lack of progress has been due more to the complexity of the problem than to dearth of interest or effort.

It is well to stress the relative futility of electromotive force measurements. Faulty interpretations based upon this kind of data have done great harm, and have in some respects falsely discredited the electrochemical theory, because of lack of alignment of such faulty scientific observances, with the result of experience. Electromotive force indicates a tendency for activity. The true quantitative measure of this activity in any cell is the current flow, and this depends as much upon the resistance of the circuit as upon the electromotive force. A combination of factors making up a rust cell of low resistence may result in a great corrosion even though the measure of electromotive force between electrodes is relatively small.

Mr. Bancroft emphasizes the factor of film formation. It is unfortunate that iron in corroding under usual exposure conditions,

Mr. Aston. does not form and automatically renew the magnetic oxide coating which is so familiar under heat conditions. If this were the case, there would be very little to the corrosion problem as related to iron and steel in customary service. Rust is a reaction product of a porous, spongy, colloidal nature, which as it forms quite generally intensifies, rather than retards, initial effects. Furthermore, experimental data support the belief that rust plays a varying rôle according to conditions of formation, and more particularly with respect to drying or exposure after formation; even reversing its electrochemical relations under different types of every-day service, or even under the periodic changes accompanying exposure to atmosphere or other equally standard services.

To my mind, the solution of the corrosion problem lies along three lines, so far as it is related to iron and steel and to the base metal only:

1. Making a more resistant base, either by adding alloying ingredients to the iron, or by removing harmful ones. This has received the major amount of attention in the past. Unfortunately, alloying agents would be as a rule required in such amounts as to make the cost prohibitive, and in turn the desired and useful physical properties of the iron are materially altered or destroyed.

2. The development of the material, probably as a result of small amounts of addition agents, which will produce the self-generating surface film which Mr. Bancroft mentions. There is some reason for belief that copper bearing steels fall in this group under certain exposure conditions. The field is of greatest importance but offers the most complexity.

3. The incorporation within the base metal of a barrier resistance which will gradually obstruct the progress of corrosion. Many of us believe that cast iron and wrought iron are of this nature and that effort expended along these lines to obtain proper character of such internal ingredients and incorporation will not be wasted on unfertile ground.

Mr. Elliott. MR. G. K. ELLIOTT.—Anyone interested in corrosion probably will agree with me that we are indebted to Mr. Bancroft as well as Mr. Buck, Mr. Speller and the others who have given publicity to the film idea in connection with corrosion and have relieved us of that abstract conception that has been rather shabbily covered by the word "inhibition." That word never stimulated the imagination or visualization, but a film is a very concrete suggestive idea. The films we have been discussing all are chemically made but I have had experience with films that were mechanically produced and have a decided bearing upon corrosion. In particular do I refer to polished surfaces. This is not an entirely new thought for I know that polished surfaces have received much attention from our fatigue-test specialists who have found the surface condition of the test bars to be so important that a few investigators have been forced to admit that they have been fatigue-testing surface finishes and not the metals. The bar with a flawless surface, or with a surface film of amorphous metal obtained by polishing, gives superior fatigue results. In another field we are advised that the so-called stainless steels are more non-corrodible when polished. I have found the same surface film obtained by polishing, or by burnishing, to protect non-ferrous metals, also. The familiar bronze with copper 85 per cent, and tin, zinc and lead 5 per cent each, doubtless to the great surprise of many users of the alloy, may be quickly and quite visibly corroded in almost any distilled water which, although practically free from solids, is frequently rich in dissolved gases and therefore fairly active. If this bronze be given an ordinary machine finish and then immersed in distilled water of the kind mentioned, it probably will show corrosion, visible through the formation of a milky cloudiness in the water surrounding the piece, in about five minutes. If the bronze be given a fine emery finish, corrosion probably will not be visible in much less than 30 minutes. If, however, the bronze piece be polished perfectly it may remain in the water indefinitely without showing the effects of corrosion although if there happen to be any imperfections in the surface film they may become the centers for small local manifestations. **Mr. Elliott.**

Another significant observation concerning this particular case of corrosion is that chemical analysis shows about 80 per cent of the metal going into the water to be lead, and further investigation reveals that this form of corrosion is peculiar to bronzes containing more than two or three per cent of lead—a pair of facts that point to something that can be put to practical use in applying bronzes to fittings, valves, and other parts for handling water, especially condensation, and steam.

Mr. Carson. MR. H. Y. CARSON.—Previous speakers have brought out an interesting point which I would like to emphasize, namely, the effect of a tenaciously adhering mechanical film as a corrosion inhibitor. Perhaps this is not new—indeed I think it would be difficult to express much that is novel in the study of corrosion. It is a fact, however, that the underlying structure, or perhaps I should say the surface structure, of iron has much to do with the holding of a mechanical film on the surface. This subject is one that has not been given any serious consideration by our Committee A-5; at least we do not find

Mr. Carson. that this phase of the corrosion subject has been set forth in the printed literature. I think the committee should make a critical comparison of highly deformed pieces of steel, perhaps selecting a specimen which is cold-rolled and others which are highly deformed but rolled above the "critical temperature" for steel. Other specimens could be selected of the same chemical analyses but which are not mechanically worked or deformed beyond the original cast structure. It will no doubt be found that these specimens, although they are of the same chemical analyses, succumb to the effects of corrosion very differently from each other. The specimens which are cast or not so highly deformed in grain structure will withstand the effect of surface corrosion and pitting much better than the other materials which possess highly deformed internal structure. Now it is very likely that an examination by the microscope of the surface and underlying structure will reveal that the undeformed interlocking formation of the grain structure explains this well-known tendency to tenaciously hold the product of corrosion itself firmly to the surface, thereby acting as a definite inhibitor to further corrosion. Furthermore, when we are discussing corrosion itself we should be careful to divide this very big subject into its various groups or types. There is an atmospheric type of corrosion which retains the mechanical film alluded to above while on the other hand there are many hydrolizing reagents such as are found in sub-aqueous conditions where there is to be found a powerful electrolytic action tending in many cases to dissolve this mechanical film of oxide and carry it off in solution. I think many investigators have not been clear in their discussions and in many instances have widely departed from each other because of the lack of appreciation that there are different types and groups of corrosion phenomena.

Mr. Thum. MR. E. E. THUM.—It might be desirable to call attention to the work which has been done during the last ten years by the Corrosion Committee of the British Institute of Metals. They have been studying almost exclusively the action of condenser tubing in salt and fresh water. For perhaps five or six years their experiments were somewhat fruitless because they were using "loss of weight" determinations almost exclusively without regard to the apparent fact that short lives of tubing were associated with deep pitting and apparent "dezincification." Of course loss of weight gives no indication whatever of the depth of pit. Long lived condenser tubes show general thinning, losing uniformly perhaps only 0.05 mm. in thickness in twenty years. Such a tube would be found to be covered by a very adherent white coating of complex character.

Mr. Thum.

Their early experiments also showed that the nature of the film first to form on a bright sample of such brasses after immersion in sea water under various conditions had a determining influence on the subsequent history of the experiment. In some cases this first film would become darker with time, finally reaching a thickness of about 0.04 mm.; it would be somewhat glazed in appearance and extremely tenacious. This film, which is really a protective film, does not seem to be wholly impervious to the corroding solution, since careful determinations of the metal which actually went into the solution plus the amount found in the loose precipitate gradually increased in amount; yet that semi-permeable film actually remained continuous and intact, and if injured in any way, reformed. An experiment extending over a great many months would show that the expected life of a tube with such a covering would be from twenty years upwards. On the other hand, samples of metals of almost exactly the same composition, having no determinable difference in the physical constitution or surface condition, when immersed in a companion beaker, would first develop a film which could not be distinguished from the other, but after a short lapse of time, specks of adherent colored salts would form here and there and grow, and in a relatively short time the original glaze would be perforated. If the adherent salts were removed, a red coppery area would be found underneath, and a localized corrosion had started at those points. Such tubes would fail very quickly indeed; and strangely enough it was found that if a certain tube developed a resistant coating, all the tubes of that particular mill order or batch would do the same thing.

In order to solve the problems presented by such observations the committee has for the last three or four years been studying the action of pure zinc, copper and the various brasses when immersed in various solutions by continuous microscopic observations. They have concluded that before immersion, metals acquire a layer of oxide or basic carbonate, and its further history in solution depends on the action of the corroding solution and the corrosion products on this film.

PHYSICAL PROPERTIES OF SOME COPPER-SILICON-ALUMINUM ALLOYS WHEN SAND CAST.

By E. H. Dix, Jr.,[1] and A. J. Lyon.[2]

Alloys of silicon and aluminum have been investigated by Roberts[3] and Fraenkel,[4] and later by the Alloys Research Committee of the Institute of Mechanical Engineers (British).[5] These men evidently studied the series from the theoretical side only, and upon finding that no better physical properties were obtainable in this series than had already been found in the better-known copper and zinc-aluminum alloys, concluded that the series was of no practical value. During the past year, the Engineering Division of the Air Service, McCook Field, Dayton, O., has found that the addition of silicon to aluminum is very advantageous as regards foundry practice. The alloys may be cast around hard cores without danger of cracking and the tendency to shrink and draw between thick and thin sections is much less than in most aluminum alloys. However, the silicon-aluminum alloys are very difficult to machine. The low-silicon alloys tear in much the same manner as pure aluminum, and the high-silicon alloys not only tear but seem in addition to very quickly dull the tools. For this reason, additions of copper were tried and found to greatly improve the machining qualities.

Material.

The ingot aluminum used in this investigation contained nearly 1 per cent of silicon and was chosen because this seemed to be a good opportunity for using a 98-per-cent grade of aluminum ingot where the only impurity in excess was silicon. Complete analysis of this ingot is as follows:

Silicon	0.99 per cent
Copper	0.32 "
Iron	0.51 "
Manganese	nil
Aluminum (by difference)	98.18 "

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[1] Chief, Metallurgical Branch, Engineering Division, Air Service, Dayton, O.

[2] Metallurgist, Engineering Division, Air Service, Dayton, O.

[3] C. E. Roberts, "The Alloys of Aluminum and Silicon," *Transactions*, Chemical Society (London), Vol. 105, pp. 1383–1386.

[4] W. Fraenkel, "Silicon-Aluminum Alloys," *Zeit. Anorg. Chem.*, Vol. 58, pp. 154–158; Abstracts, *Chem. Zentralbl.*, Vol. 11, p. 143.

[5] The Eleventh Report of the Alloys Research Committee to Institute Mechanical Engineers (British).

The silicon was added in the form of a silicon-aluminum hardener purchased from the Electrometallurgical Corporation, Niagara Falls, N. Y. The following analysis was obtained:

Silicon	60.51 per cent
Copper	0.30 "
Iron	1.22 "
Aluminum (by difference)	37.97 "

The copper was introduced in the form of a 50-50 copper-aluminum hardener made in our own foundry and having the following chemical analysis:

Copper	49.55 per cent
Silicon	0.17 "
Iron	0.21 "
Aluminum (by difference)	50.07 "

FOUNDRY PRACTICE.

The fifteen alloys were made up in melts of 40 lb. each. The aluminum ingot, copper-rich hardener and silicon-rich hardener were all charged together in a No. 40 plumbago crucible and melted in an Iler oil-burning furnace. The temperature was measured by a chromel-alumel thermocouple without a protecting tube, used in conjunction with a Hoskins high-resistance millivoltmeter. The method of making the alloys was maintained uniform throughout the series, each melt being carried to just under 1400° F. with frequent stirring. The pouring temperature was maintained at 1300° F. ± 20° F. The time in the furnace averaged about one hour. No flux of any kind was used. All of the test bars were poured from the original melt except the modulus of elasticity specimens, which were cast from a remelt in most cases.

In order to test the effect of silicon on the cracking tendency of the alloys, a hot shortness test was devised. This consisted in casting, in green sand, test bars with enlarged bosses at each end, around pins spaced 12 in. apart and firmly fixed in a heavy iron plate. The test bar was ½ in. in diameter over a length of about 2½ in. and then tapered gradually to a diameter of 1 in. at each end. The metal was led into one end of the test bar and risers were placed over each boss.

In order to obtain the pattern shrinkage of these alloys, test bars 1 in. square were cast in green sand molds containing graphite blocks at the ends, adjusted to exactly 12 in. between faces. Three test bars were cast for each melt. When cold their length was measured by a micrometer caliper and the difference between this length and their original length of 12 in. was taken as the shrinkage in inches per foot.

The test bars for physical testing were cast according to the standard practice of the Engineering Division, which consists in casting all bars horizontally in green sand with the mold slightly tilted so that the metal runs up hill. The metal is poured into a pouring sprue $1\frac{1}{4}$ in. in diameter and through gates into the test bars which are joined at the opposite end to a riser $1\frac{1}{4}$ in. in diameter. A 3-in. cope is used in all cases. The bars which were tested "as cast" were cast three in a mold. The bars tested "machined" were cast in a similar manner except that $\frac{1}{8}$ in. machining allowance was made. The modulus of elasticity bars were cast two bars in a mold, $\frac{3}{4}$ in. in diameter over the gage length and tested without machining. The bars for the impact test were cast $\frac{9}{16}$ in. square by 9 in. long. Four bars were cast in one mold and three specimens machined from each bar. The bars for coefficient of expansion tests were cast $\frac{3}{4}$ in. in diameter, two in a mold.

TESTING PROCEDURE.

Physical Testing.—The physical tests were carried out under the supervision of Mr. R. R. Moore.

Tension tests were made on the bars "as cast" in a 20,000-lb. Olsen testing machine, using wedge grips. Five bars of each melt were tested. Elongation was measured over a 2-in. gage length, the diameter of which was approximately $\frac{1}{2}$ in. Specimens for modulus of elasticity tests were threaded and held in self-aligning adapters. The deformation was measured by a Ewing extensometer. Two bars of each melt were tested. The high temperature tests were made on $\frac{1}{2}$-in. diameter bars without removing the skin over the gage length, although the ends were threaded for self-aligning adapters. The tests were made in a Hoskins tube furnace. The temperature was obtained by a chromel-alumel couple attached to the center of the specimen and used in conjunction with a Leeds & Northrup potentiometer. Three tests were made at both 300 and 600° F. The impact tests were made in the Charpy pendulum machine with a light-weight hammer having one-tenth the capacity of the standard hammer.[1] The standard 10-mm. square specimen with round drilled notch 5 mm. deep and having a radius of 1 mm. was used. Twelve tests were made from each melt. The Brinell, scleroscope, and specific gravity tests were made on the end of all specimens tested "as cast"; a 500-kg. load was used in the Brinell test. The coefficient of expansion tests were made by the Bureau of Standards on one bar from each melt.

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[1] E. H. Dix, Jr., "Charpy Impact Test as Applied to Aluminum Alloys," *Mining and Metallurgy No. 160*, Section 3, April, 1920.

Chemical Analysis.—Chemical analyses were made on all melts according to standard methods, under the supervision of Mr. M. R. Whitmore, and are given in Table I.

Metallographic Analysis.—Specimens for metallographic analysis were cut from the riser end of the bars to be tested "as cast" so that the structure is that of a $\frac{3}{4}$-in. diameter bar cast in green sand. No annealing was done. The specimens were prepared in the usual manner, except that the final polishing was accomplished by means of heavy magnesia powder and distilled water. The following etching reagents were tried: (1) 2.5-per-cent hydrofluoric acid, (2) 0.1-per-cent sodium hydroxide, (3) 20-per-cent nitric acid at 70° C., followed by quench in cold water and (4) 5-per-cent hot nitric acid. These reagents were found unsatisfactory except for special purposes, the structure being much more clearly revealed by careful polishing without etching.

TABLE I.—CHEMICAL ANALYSES.

Added Percentages.			Analysis, per cent.			
Copper.	Silicon.	Manganese.	Copper.	Silicon.	Iron.	Manganese.
0	0	0	0.32	0.99	0.51	Nil
0	3	0	0.41	4.12	0.59	"
0	6	0	0.42	6.20	0.90	"
0	9	0	0.34	9.34	0.73	"
2	3	0	2.15	2.66	0.62	"
2	6	0	2.32	6.69	0.65	"
2	9	0	2.29	9.58	0.71	"
4	3	0	4.25	3.41	0.74	"
4	6	0	4.17	4.92	0.72	"
4	9	0	4.26	10.12	0.70	"
6	3	0	6.39	3.90	0.77	"
6	6	0	6.39	6.28	0.51	"
6	9	0	6.29	9.00	0.66	"
2	3	1	2.33	3.86	0.65	0.87
2	6	1	2.40	9.97	0.63	0.67
2	9	1	2.20	9.56	0.97	0.71

DISCUSSION.

Physical Tests.—The results of the physical tests are summarized in the form of curves, Figs. 1 to 7, inclusive, which are self-explanatory. The results of tensile strength, elongation and hardness tests given in these figures were obtained within 24 hours of casting but specimens tested one month later showed practically the same results. These results were obtained on specimens "as cast"; but tests were also made on machined specimens and these showed an average tensile strength 860 lb. per sq. in. lower than those tested with the skin on.

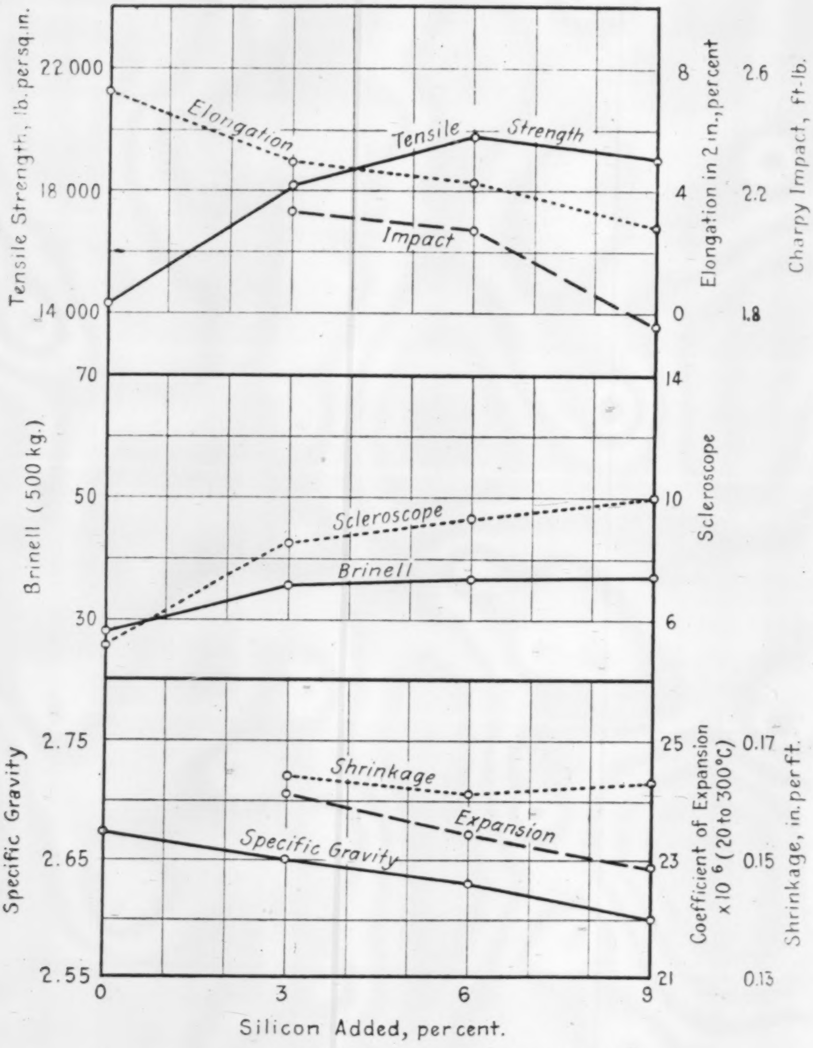


FIG. 1.—Effect of Additions of Silicon to Aluminum.

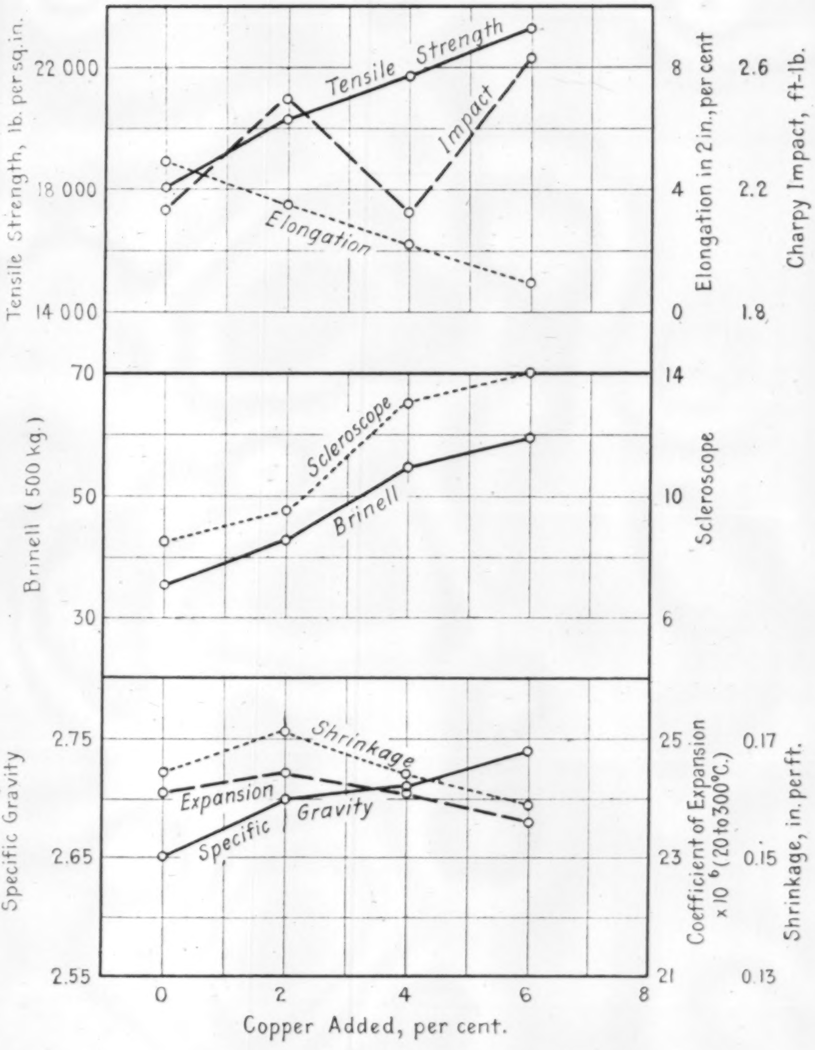


FIG. 2.—Effect of Additions of Copper to 3-per-cent Silicon Alloy.

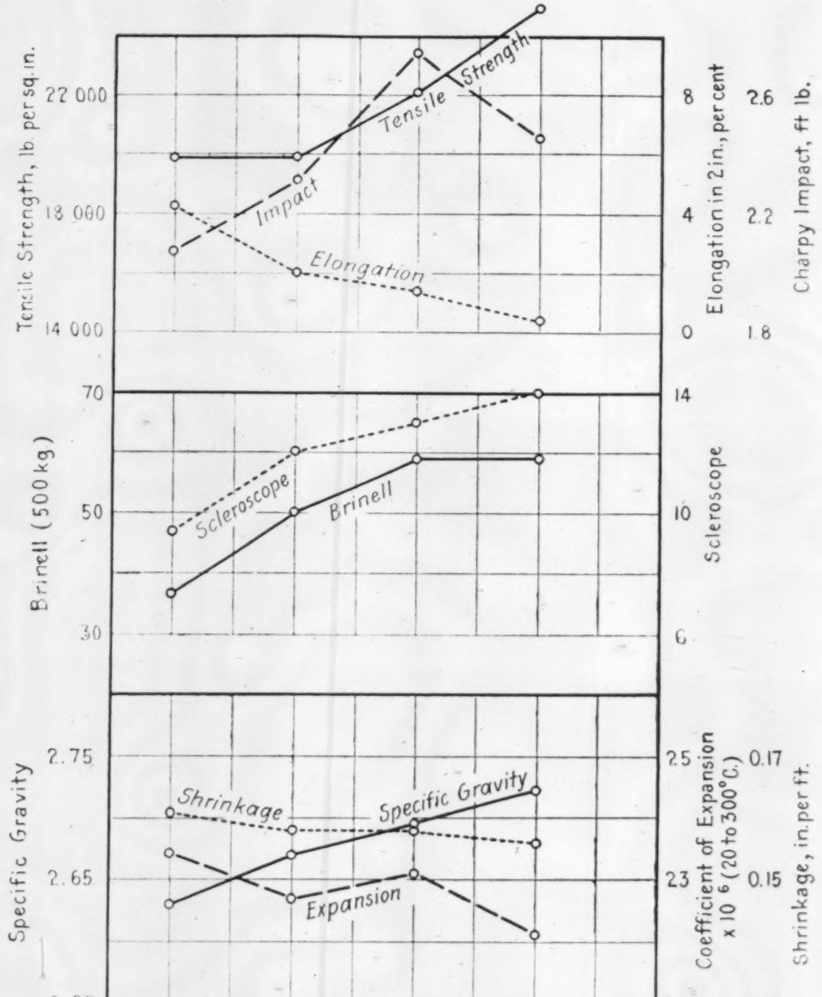


FIG. 3.—Effect of Additions of Copper to 6-per-cent Silicon Alloy.

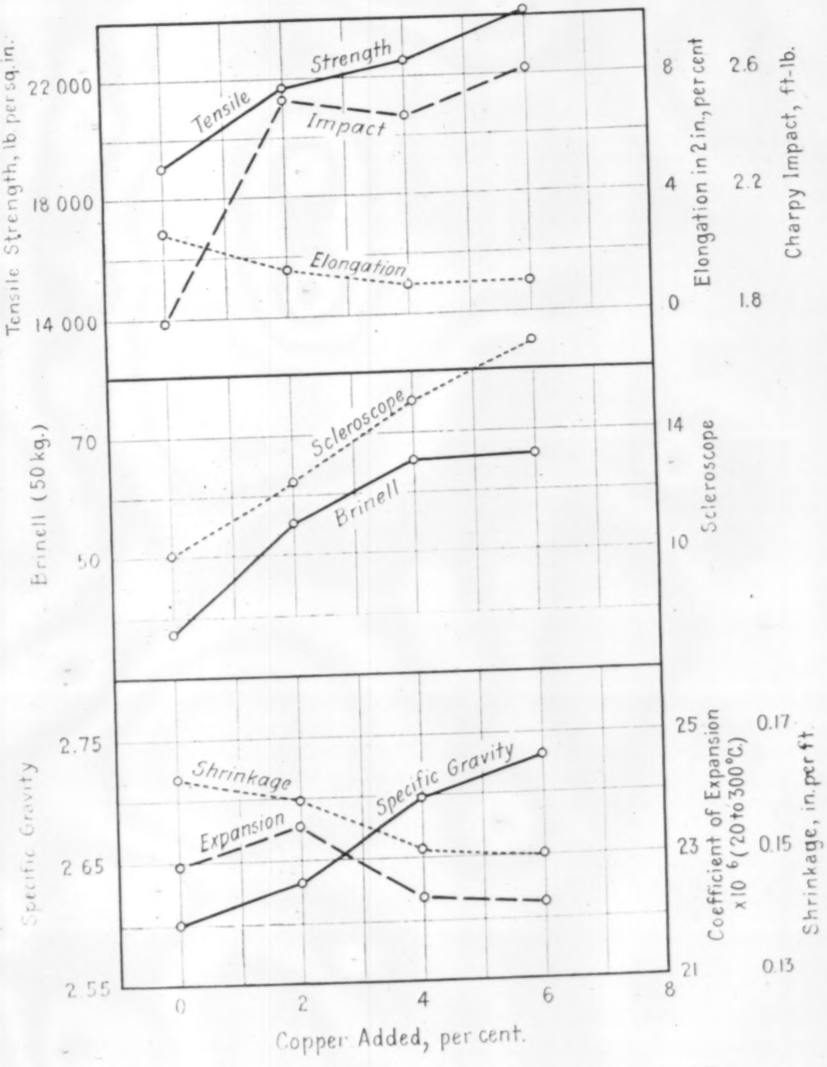


FIG. 4.—Effect of Additions of Copper to 9-per-cent Silicon Alloy.

From Fig. 1 it is evident that the added silicon content should be between 3 and 6 per cent. It should be borne in mind that the original ingot used in these experiments contained 0.6 to 0.7 per cent more silicon than normal. When copper is added to the silicon alloys, it seems desirable to keep the silicon content near the lower limit given above, inasmuch as the alloys become less ductile with increasing silicon and the increase in strength is very slight. Four per cent of copper seems to be the maximum advisable to use with the silicon alloys.

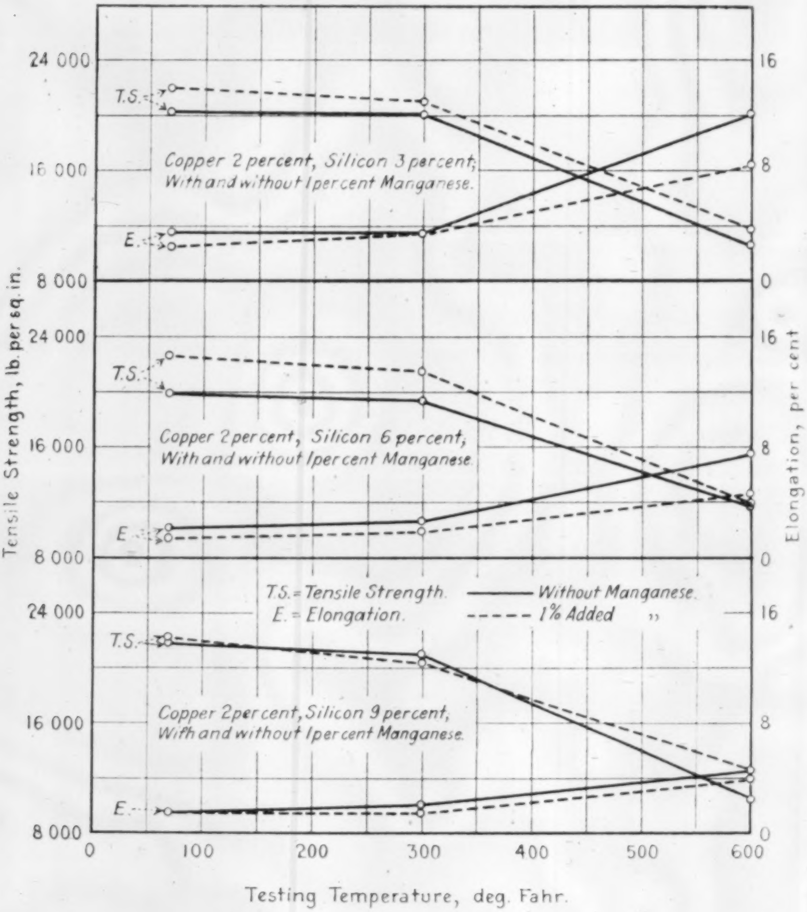


FIG. 5.—Temperature Tests. Effect of Additions of 1 per cent of Manganese to Silicon Alloy.

Referring to Fig. 7, it will be noted that in the alloys without copper, silicon has the effect of stiffening the curve beyond the apparent elastic limit, which is also raised. With a constant silicon content of 6 per cent, additions of copper also have a stiffening effect on the modulus curve beyond the apparent elastic limit. The modulus

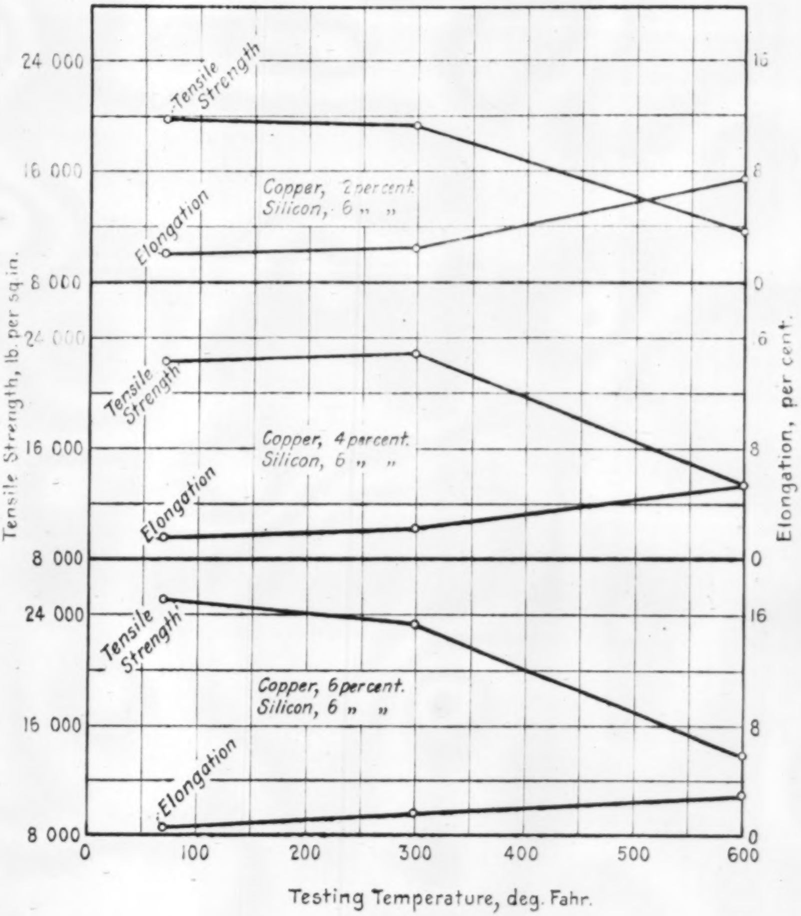


FIG. 6.—Temperature Tests. Effect of Additions of Copper to 6-per-cent Silicon Alloy.

of elasticity of this series is between 10,000,000 and 11,000,000 lb. per sq. in. Thus there are several desirable combinations which may be chosen with the copper and silicon, both between the limits of 3 to 5 per cent. If good elongation is desired without particular machining qualities the copper should be low. Where fine threads must be cut, or good machining qualities are desired for some other reason, the copper should be near the upper limit and the silicon low.

The effect of manganese as shown by Fig. 5 seems to be to raise the tensile strength at the expense of the elongation, but it does not seem to impart any particular resistance to high temperatures, as it is known to do with the straight copper-aluminum alloys.

Figs. 5 and 6 show that the straight copper-silicon-aluminum alloys will hold their strength with only a slight decrease up to 300° F. and the strength at 600° F. is about that obtained from the higher copper alloys, say 10 to 12 per cent.

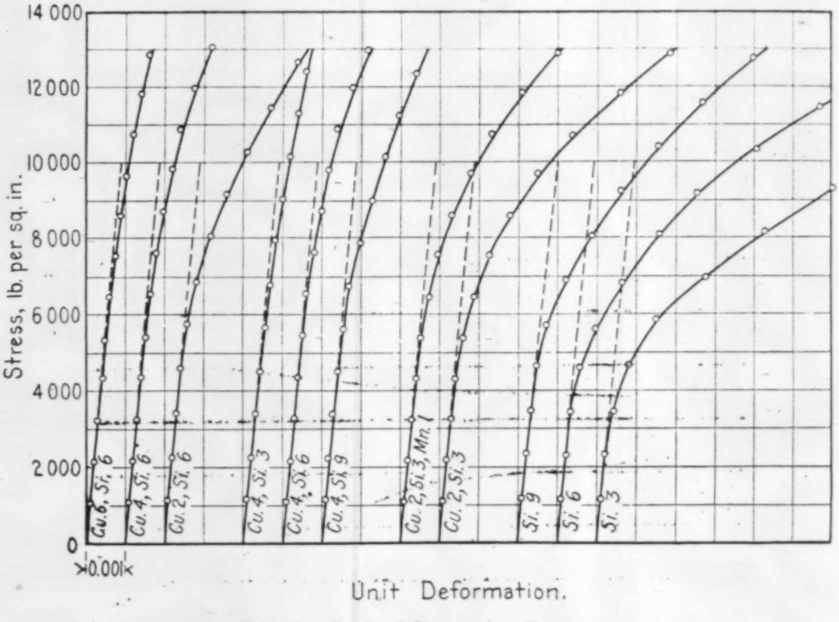
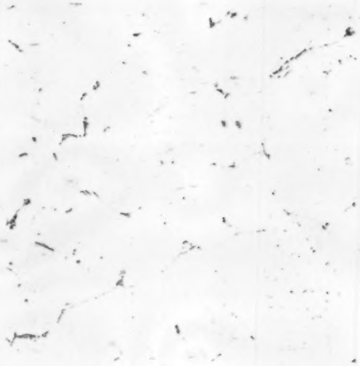
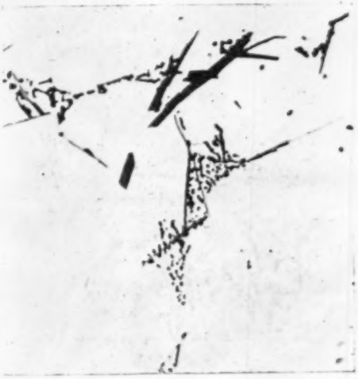


FIG. 7.—Stress-Deformation Curves.

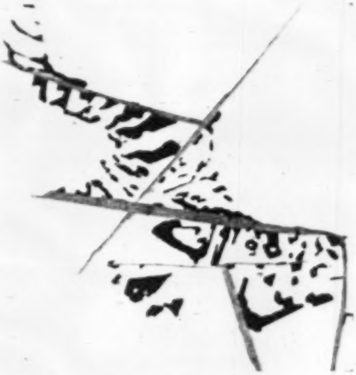
The most interesting feature of the whole series is that only one bar cracked in the hot-shortness test. This was from the melt containing 6 per cent of copper and 9 per cent of silicon. All of the others withstood this test without sign of cracking. They were then pulled in the ordinary way and showed a tensile strength slightly higher than the average for their melt and an elongation slightly less. This is considered quite remarkable, inasmuch as a number of other aluminum alloys have been subjected to the same test and all have cracked in



(a) × 100

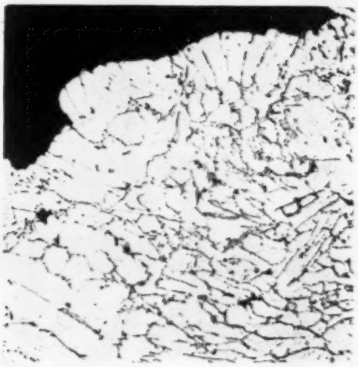


(b) × 500

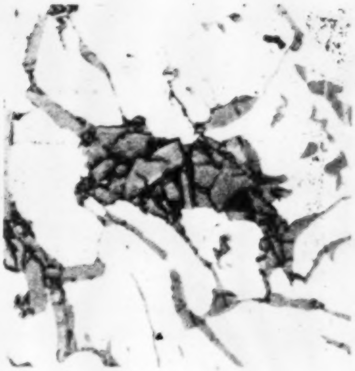


(c) × 1000

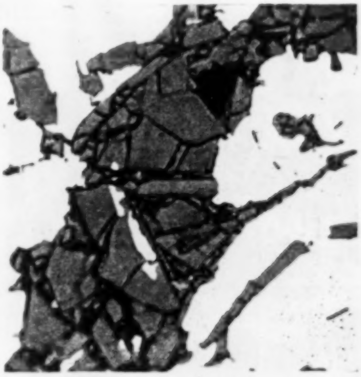
FIG. 8.—Average Structure.



(a) × 100



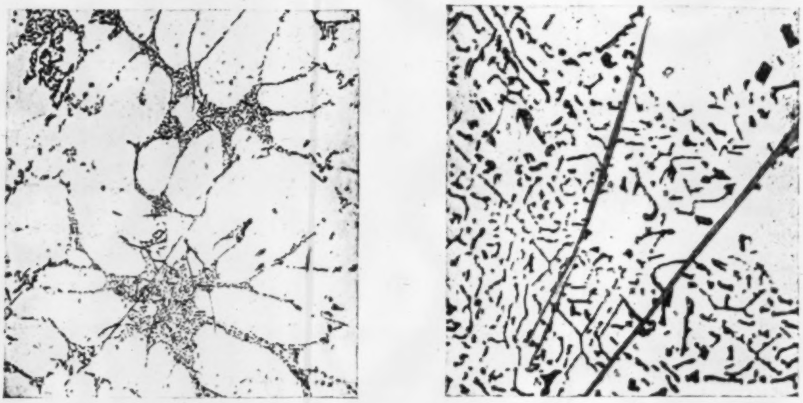
(b) × 500



(c) × 1000

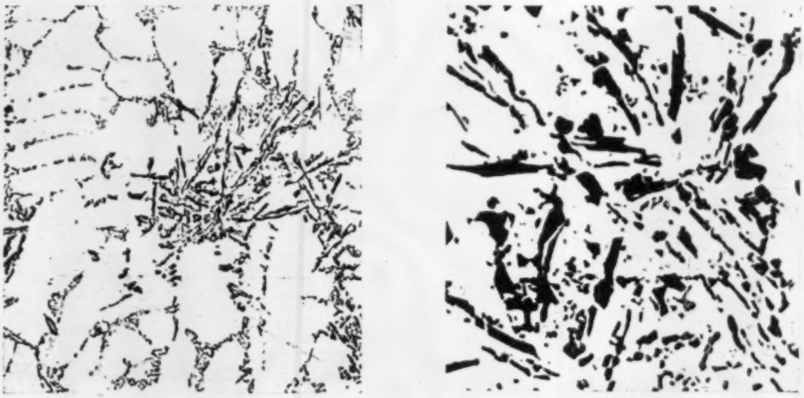
FIG. 9.—Segregated Area Adjacent to Pipe.

PLATE I.—Aluminum Ingot Containing 0.99 per cent of Silicon, 0.51 per cent of Iron, and 0.32 per cent of Copper as Impurities. Unetched.



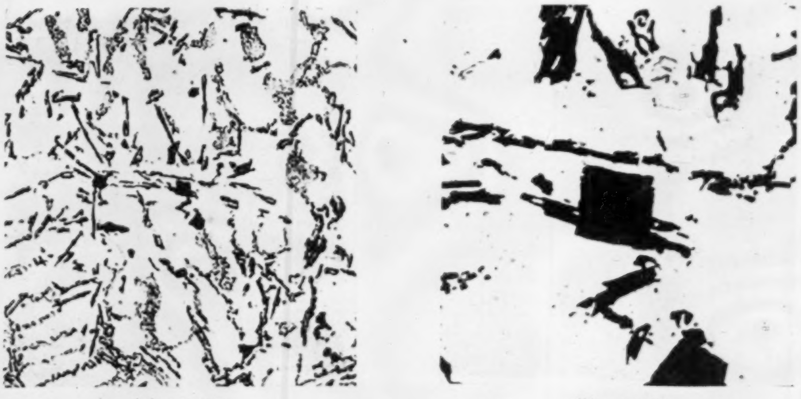
(*a*) × 100 (*b*) × 500

FIG. 10.—3 per cent of Silicon.



(*a*) × 100 (*b*) × 500

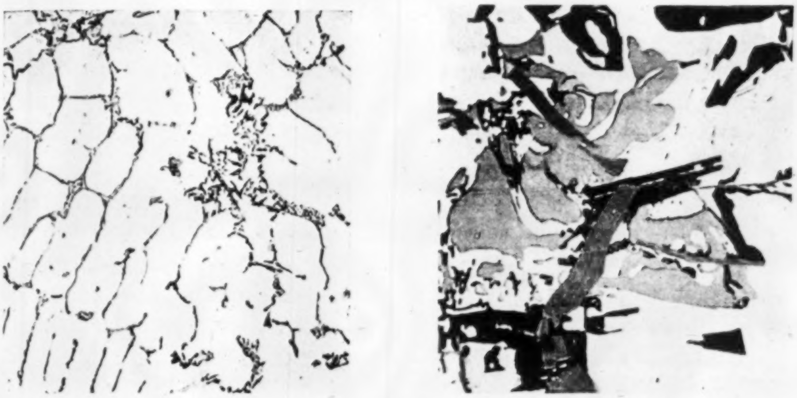
FIG. 11.—6 per cent of Silicon.



(*a*) × 100 (*b*) × 500

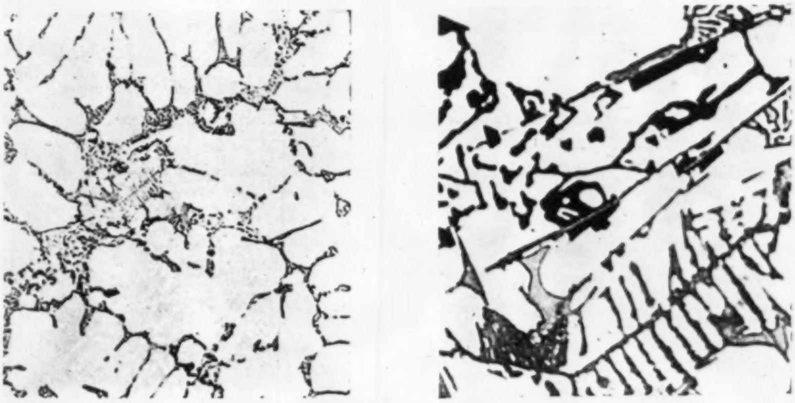
FIG. 12.—9 per cent of Silicon.

PLATE II.—Aluminum with 3, 6 and 9 per cent of Added Silicon. Unetched.



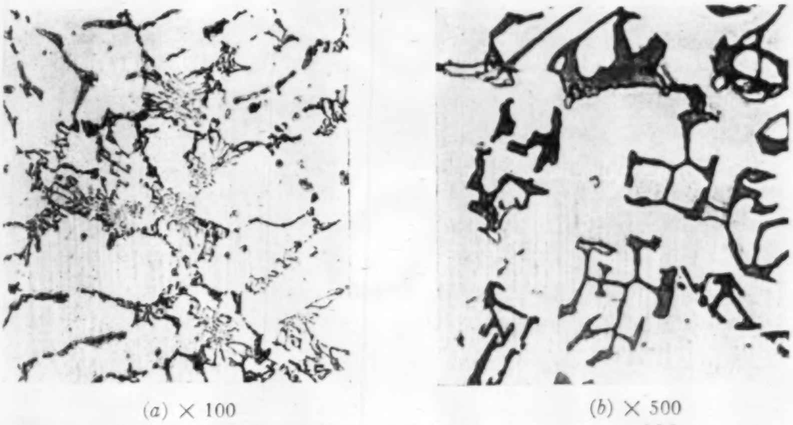
(*a*) × 100 (*b*) × 500

FIG. 13.—3 per cent of Silicon, 4 per cent of Copper.



(*a*) × 100 (*b*) × 500

FIG. 14.—3 per cent of Silicon, 6 per cent of Copper.



(*a*) × 100 (*b*) × 500

FIG. 15.—3 per cent of Silicon, 2 per cent of Copper, 1 per cent of Manganese.

PLATE III.—Aluminum Containing 3 per cent of Silicon with Added Copper, with and without Manganese. Unetched.

the mold. This cannot be explained on the grounds of low shrinkage or of low coefficient of expansion, for as the curves show, these properties do not differ greatly from the more common aluminum alloys.

It should be emphasized that the results of this investigation were obtained without the use of any flux or the introduction of alkali metals, by a simple mixing of metals according to well established foundry practice which may be carried out with ease in any small foundry. An alloy may be thus made having physical properties equal or superior to No. 12 alloy[1] and having much better casting qualities than any aluminum alloy with which we have had experience.

Metallographic Study.—In Plate I, Fig. 8 (*a*) shows the average structure of a specimen of the aluminum ingot used in this investigation. The impurities silicon and iron form a network structure. Fig. 9 (*a*) shows a segregated area adjacent to a pipe near the center of the specimen. A comparison of this with Fig. 8 (*a*) gives an indication of the extreme care which should be exercised in taking a chemical sample. Figs. 8 (*b*) and (*c*) are of the same area as Fig. 8 (*a*) at 500 and 1000 diameters respectively. The fine eutectic appears blue-gray in color in the unetched specimen, and has been definitely identified as the silicon-aluminum eutectic. The needles appear a light gray in the unetched specimen and are characteristic of what has been described as $FeAl_3$ in both form and color. The copper present is in solid solution. Figs. 9 (*b*) and (*c*) are of the same area as Fig. 9 (*a*) but taken at 500 and 1000 diameters. The irregular masses and strings which show gray in these figures are the same color as the needles shown in Figs. 8 (*b*) and (*c*). It is thought that this may be the constituent that is described by Merica[2] and Eleventh Report of Alloys Research Committee[3] as constituent "X." It may be observed that the segregate consists mostly of this constituent. Chemical analysis is being made of a sample taken from this portion of the bar, but the results are not yet available.

Plate II shows the effect on the microstructure of increasing the amounts of added silicon. Fig. 10 (*a*) (silicon 3 per cent) shows the average structure at 100 diameters and (*b*) the blue-gray silicon-aluminum eutectic and needles of the iron constituent at 500 diameters magnification. Fig. 11 (*a*) shows the average structure with 6 per cent added silicon and (*b*) shows at 500 diameters some of the silicon-aluminum eutectic appearing in a coarser form. This appears somewhat darker than the fine eutectic in (*a*), but under higher magnification it has the same coloring. Fig. 12 shows the effect of 9 per cent added silicon. In addition to the silicon-aluminum eutectic and iron constituent, there is a third constituent which appears a bluish gray of a somewhat different shade from the silicon eutectic and usually appears in cubes such as are shown in Fig. 12 (*b*). This constituent has been observed in practically all the specimens of this series examined, but is more plentiful in the melts containing 9 per cent of added silicon. This constituent may be primary silicon or it may be due to some impurity in the silicon-rich hardener used.

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[1] Composition: Copper, 8 per cent; aluminum, 92 per cent.

[2] P. D. Merica, R. G. Waltenberg, and J. R. Freeman, Jr., "The Constitution and Metallography of Aluminum and Its Light Alloys with Copper and with Magnesium," *Scientific Paper No. 337*, U. S. Bureau of Standards, 1919.

[3] The Eleventh Report of the Alloys Research Committee to Institute Mechanical Engineers (British)

Plate III, Figs. 13 and 14, shows the effect of copper on the microstructure of the 3-per-cent silicon alloy. Fig. 13 shows in addition to the dark silicon-aluminum eutectic, a lighter eutectic globular in form which appears bright with a faint pink tinge in the unetched specimen, and is colored brown by Hanson's HNO_3 quench, both of which identify it as $CuAl_2$. The needles and the peculiar skeleton structure in Fig. 14 are identical in color and are not attacked by hydrofluoric acid or either 5 or 20-per-cent solutions of hot nitric acid, or by a 0.1-per-cent solution of sodium hydroxide. According to Hanson,[1] the $FeAl_3$ may be identified by the use of a 5-per-cent solution of hot nitric acid or hydrofluoric acid, but the results were all negative in this investigation.

In Plate III, Fig. 15, a constituent appears in half tone which cannot be distinguished in color from what has been referred to as constituent "X." However, the particular form in which it occurs has only been observed where manganese in addition to copper and silicon are used as added elements in this series. Fig. 15 (*b*) shows the characteristic swastika form.

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[1] D. Hanson and S. L. Archbutt, "The Micrography of Aluminum and Its Alloys," *Journal of the Institute of Metals*, Vol. XXI, No. I, 1919.

FATIGUE OR PROGRESSIVE FAILURE OF METALS UNDER REPEATED STRESS.

By H. F. Moore,[1] J. B. Kommers,[2] and T. M. Jasper.[3]

The failure of metal parts of machines after thousands or millions of repetitions of a load, which for a time apparently does no damage, is a phenomenon which for over half a century has been of interest to materials engineers and which, since the use of high-speed machinery under heavy service has become wide-spread, is one which is of prime importance. The term "fatigue" has been applied to such failure, and the generally accepted idea of the mechanism of fatigue failure is that of the progressive spread of a minute crack, or of a plane of cleavage, from some nucleus. The nucleus may be a minute region of high localized stress (the root of a screw thread, for example), or a minute flaw or region of weakness in the structure of the metal.

Fatigue failures in metal ***structures*** (structures as distinguished from machines) are rare. Usually in structural parts failure, when it occurs, is due to stressing a considerable amount of metal beyond the limit where appreciable plastic action begins, and the consequent serious distortion of the part, or in extreme cases the collapse or tearing apart of the structure.

It should be noted that for machine parts or structural members subjected to a few loads, localized stresses or localized weakness of material are rarely of importance, while for machine parts or structural members subjected to oft-repeated loading such localized stresses or localized weakness may be of the utmost importance. Many failures of machine parts are the result of a combination of fatigue action, due to oft-repeated working loads, and damage caused by occasional overstress.

Apparatus and Specimens for Repeated-Stress Tests.

A testing machine for making tests under repeated stress should be so designed as to produce rapid repetitions or reversals of a definite known unit stress in a test specimen. It is highly desirable that the stress produced should not vary greatly with slight changes of speed, as very few commercial power circuits will drive motors day after day with speed variations less than 5 per cent.

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[3] Engineer of Tests, Joint Investigation of the Fatigue of Metals.

Specimens for repeated-stress tests should be so designed that there is no localization of high stress whose magnitude cannot be computed accurately. This feature is much more important for repeated-stress specimens than it is for "static" test specimens. It is especially important to avoid sharp reëntrant angles and sharp notches in such specimens. If specimens with sharp notches are used it should be recognized that the test results will be empirical, and that the stress set up cannot be computed with any considerable degree of accuracy.

As typical examples of apparatus and specimens for repeated-stress testing, testing machines and specimens used in the Joint Investigation of the Fatigue of Metals[1] will be described briefly.

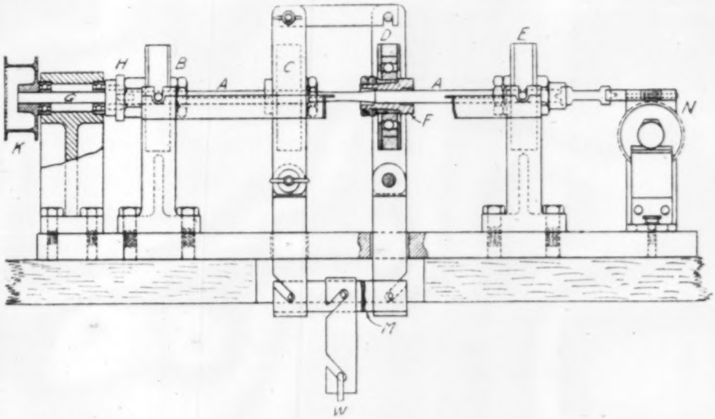

FIG. 1.—Diagram of Rotating-Beam Type Testing Machine for Tests Under Reversed Stress.

The testing machine most widely used is shown in Fig. 1. This machine is of the rotating-beam type, and during one rotation there takes place a complete cycle of reversed stress in the specimen between *C* and *D*, the stress varying from tension to compression. The machine used is a slight modification of the one described before this Society in 1919 by F. M. Farmer,[2] and is sometimes spoken of as the "Farmer" machine. This machine was chosen because it is a machine by means of which definite, measurable unit stresses can be set up in a properly designed specimen; because, as was shown by tests at Illinois and elsewhere, the test results are not appreciably affected by a considerable variation in speed; because it can be run at fairly high speeds (1500 r.p.m. was the regular speed used) with very slight vibration; and because its cost was low enough to allow the purchase of a battery of fifteen machines with the funds available.

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[1] The first published report of the work of the Joint Investigation of the Fatigue of Metals gives a much more detailed account of the first stages of that investigation than can be given in this paper. That report is issued as *Bulletin No. 124* of the Engineering Experiment Station of the University of Illinois, and in a slightly abridged form as Publication No. 4 of the Engineering Foundation, New York.

[2] *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II, p. 709 (1919).

For studying the effect of repeated stress which is not completely reversed the machine shown in Fig. 2 is used. This is called the tension-bending machine. In this machine the specimen *Q* is a rotating cantilever beam loaded at the end *A*. This end load would produce completely reversed stress in the specimen, but the compressive stress is partly or wholly offset by tensile stress set up by the spring *S* which rotates with the specimen. The pressure of the spring is transmitted to the specimen at each end by means of crossed-knife edges *K′K″*, which practically eliminate any bending action due to the pressure of the spring itself. The maximum unit stress to which any surface fiber of the specimen is subjected is equal to the sum of the steady tensile unit stress due to the spring and the maximum unit tensile stress due to the end load *P;* the minimum unit stress to which any surface fiber of the specimen is subjected is equal to the difference of the steady tensile unit stress due to the spring and the maximum compressive unit stress due to the end load. The normal speed of this machine is 1500 r.p.m.

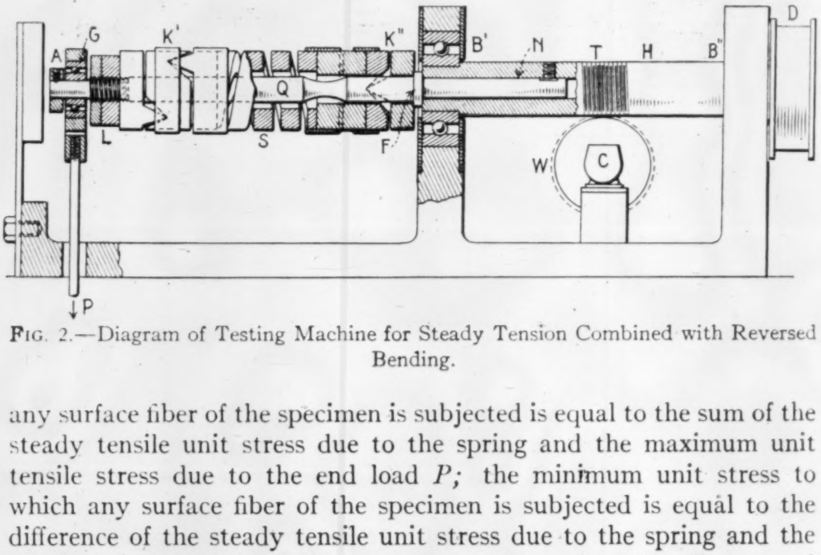

Fig. 2.—Diagram of Testing Machine for Steady Tension Combined with Reversed Bending.

Auxiliary tests under reversed flexural stress were made on an Upton-Lewis testing machine.

The two machines described in the foregoing paragraphs produce tensile and compressive stresses in the specimen. It is obvious that in investigating the effect of repeated stress, repeated shearing stress should be studied as well as repeated tensile stress and repeated compressive stress. This can best be done by a machine for producing repeated torsion, since under torsion a shearing stress is set up in a specimen. Some tests were made in reverse torsion using an Olsen-Foster machine. Another form of machine for producing reversed torsion has been developed and is now in operation. This machine is shown in Fig. 3. The specimen *S* is attached at one end to the rotating head *H*, and at the other end to a rotating flexible beam *B*. At the end of this beam a load *P* is applied, by means of weights or a spring balance, through the ball bearing *R*. When the axis of the specimen is horizontal and the specimen is on the left hand side of the shaft (as seen in Fig. 3) the twisting moment on the specimen is counter-clockwise; when the shaft of the machine has rotated 180 deg. and the specimen is on the right hand side the twisting moment is clockwise; there is a complete reversal of torsional (shearing) stress during a rotation. Knowing the length of the flexible beam *B*, the weight at the end *P* and the moment set up in the specimen by the weight of the beam, the torsional moment and the shearing unit stress in the specimen can be computed. The beam *B* is made flexible, especially in one direction, to minimize vibration, and a dash pot *D*

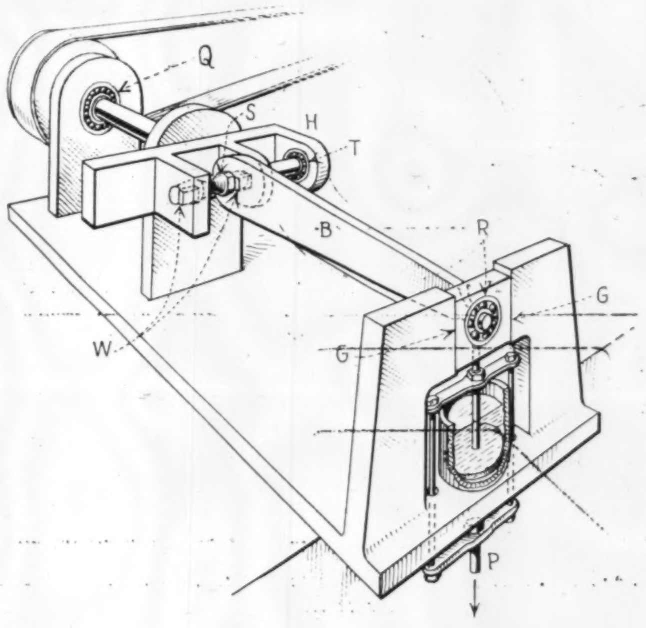

FIG. 3.—Diagram of Reversed Torsion Testing Machine.

is also of service in this regard. This machine is operated at a speed of 1000 r.p.m.

Fig. 4 shows a testing machine for producing reversals of direct axial stress (tension and compression) in a specimen. This machine has only recently been put in operation, and its usefulness has not been fully demonstrated. A calibrated spring *S* is vibrated back and forth by means of the eccentric *E* and the connecting rod *R*. The specimen *T* forms a part of the connecting rod, and hence as the spring is vibrated back and forth is subjected to alternate tension and compression. The throw of the spring and hence the maximum stress in each direction on the specimen is measured by micrometers *M′*, *M″*. The throw of the spring is nearly constant, and the magnitude of the stress can be varied by moving the fulcrum block *F* up and down, changing the effective length of the spring. The position of the fulcrum is indicated by the pointer *P* on the scale *Q*. The length of the connecting rod can be altered by means of the turnbuckle *B;* this does not alter the total throw of the eccentric, but does alter the ratio of tension to compression during a revolution of the shaft of the machine. Either a cycle of stress involving complete reversal of stress or a cycle of stress involving any desired ratio of tension to compression may be used, as may be desired. The elastic curve of the

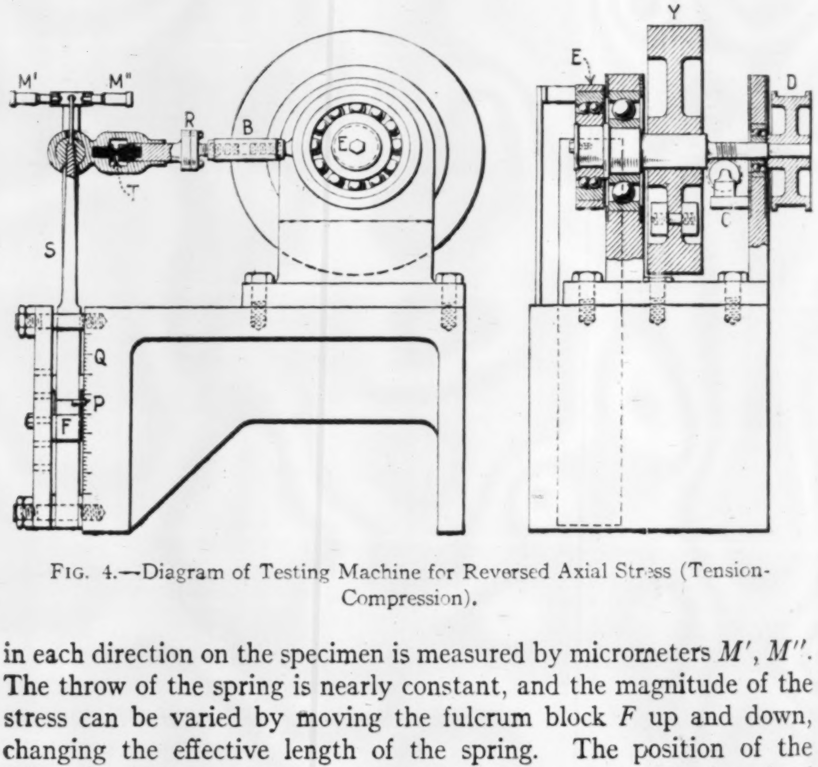

FIG. 4.—Diagram of Testing Machine for Reversed Axial Stress (Tension-Compression).

loaded spring has been determined both for slow operation of the machine by hand, and for operation at a speed of 500 r.p.m. Within the limits of observation the elastic curve for both conditions was the same.

Fig. 5 shows a testing machine for measuring the rise of temperature under a short application of repeated stress. This rise of temperature has been found to be a reliable index of the limiting reversed stress which a material can withstand without failure after millions of repetitions. The specimen *S* is held firmly by one end in the vise *V*. The other end of the specimen is held in the bearing *B* which rotates with the head *H*. By means of a screw *C* the bearing *B* can be given any desired eccentricity causing the end of the specimen to "wobble" as the shaft *T* is rotated. To calibrate eccentricity in terms of unit stress the specimen is loaded by means of a series of known weights hung at *A* and the corresponding deflections measured by means of the micrometer dial *M*. From the loads and the dimensions of the specimen the unit stresses can be calculated, and then a diagram drawn showing the relation of unit stress to deflection. To set up any desired stress in a specimen the eccentricity is adjusted until the deflection is that corresponding to the desired unit stress; then the micrometer dial is removed and the machine run. The rise of temperature under stress is measured by means of a pair of differentially-connected thermo-couples (copper-constantan). One is held by friction tape against the specimen at Q', the point of maximum stress, and the other is held against the specimen at Q'', where the stress is zero. From the couples, wires lead to a mirror galvanometer. Heat

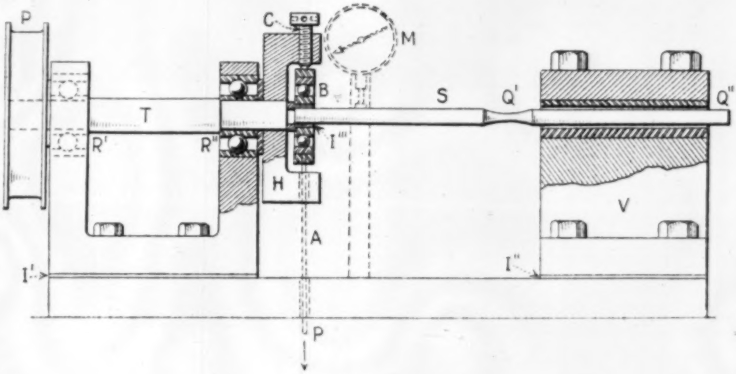

FIG. 5.—Diagram of Testing Machine for Determining the Endurance Limit by Measurement of the Rise of Temperature Under Reversed Bending.

insulation at I', I'', and I''' prevents the transfer of any appreciable quantity of heat from the bearings to the specimen. In making a test the machine is adjusted to give a low stress, and is then run at 1000 r.p.m. for a short time (usually one minute for steel) and the rise of temperature noted, then the stress is slightly increased and another run made; this process is repeated until a considerable rise of temperature (say, about 0.1° C.) is noted. In Fig. 14 (right hand part) is shown the stress-temperature diagram giving the results of such a test.

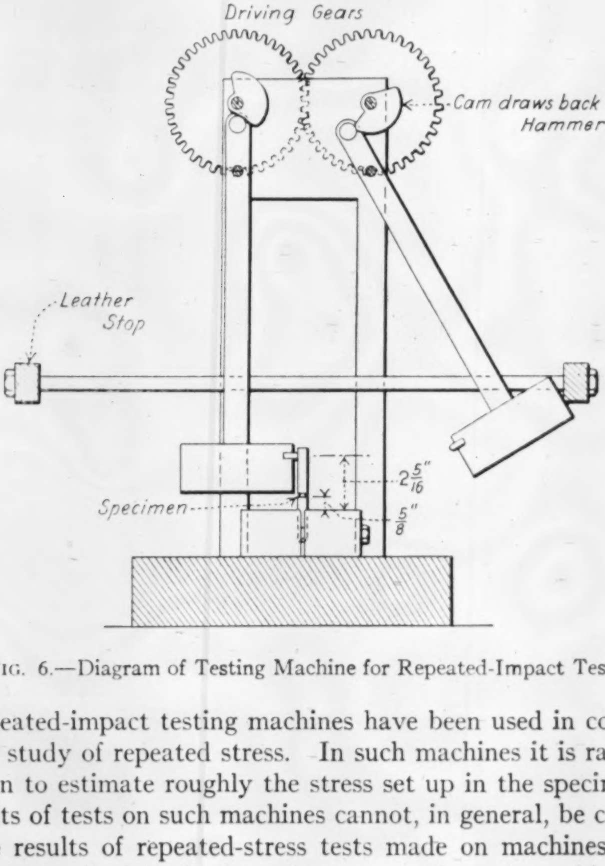

Fig. 6.—Diagram of Testing Machine for Repeated-Impact Tests.

Repeated-impact testing machines have been used in connection with the study of repeated stress. In such machines it is rarely possible even to estimate roughly the stress set up in the specimen, and the results of tests on such machines cannot, in general, be correlated with the results of repeated-stress tests made on machines such as have been described in the foregoing paragraphs. A machine of this type was used as an auxiliary machine in the Joint Investigation of the Fatigue of Metals, and it is shown in Fig. 6. Two hammers of equal weight are so operated by cams that they strike alternate blows in opposite directions against a specimen, which is a notched cantilever beam. Each hammer delivers a blow of about 0.33 ft-lb. energy at the rate of 65 blows per minute, so that there are delivered against the specimen 65 double blows per minute. The striking velocity of the hammers is 3.25 ft. per second.

Figs. 7 to 10 show the test specimens used for repeated-stress tests. Fig. 7 shows the specimen used for tests on the rotating-beam (Farmer) machine. Attention is called to the avoiding of sharp corners and small fillets. It was found better to reduce the specimen at the center by means of a tool swung on a radius than by means of small fillets and a straight portion, as in the latter case failure always occurred at the junction of straight part and fillet. It has been found necessary to reduce the specimen about in the proportion shown to insure freedom from failure due to localized stress where the bearings carrying the weights rest on the specimen. The unit stress in the specimen is calculated by the usual flexure formula, and the correctness of this determination was checked by two special tests: (1) a test on a specimen made of celluloid using Coker's polarized light apparatus (this test was made at the laboratories of the General Electric Co.), and (2) a test on a large specimen geometrically similar to that shown in Fig. 7 on which measurements of strain were taken by means of a Berry strain gage. Both these tests showed good agreement between the stress computed by the usual flexure formula and the stress corresponding to the strain observed in the special test.

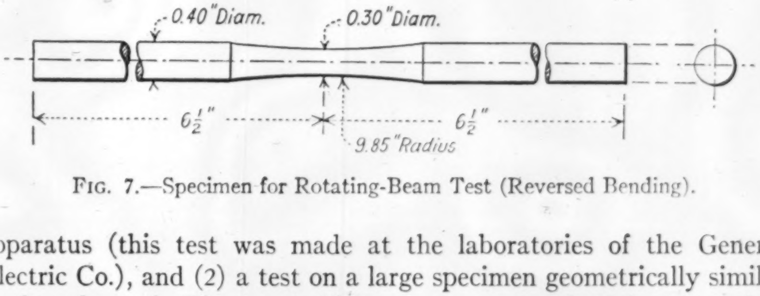

FIG. 7.—Specimen for Rotating-Beam Test (Reversed Bending).

Fig. 8 shows a specimen for the combined tension-reversed bending machine (Fig. 2), Fig. 9 shows a specimen for the reversed-torsion machine (Fig. 3), and Fig. 10 shows a specimen for the direct compression-tension machine (Fig. 4). In all these specimens care has been taken to avoid sudden changes of outline and sharp reëntrant angles.

Repeated stress specimens were given a final polish with No. 00 emery cloth over the critical section. Rough machined surface finish was shown by tests to decrease by as much as 15 per cent the strength of a steel under repeated stress. No. 00 emery paper seemed to give almost as good results as did rouge finish.

Table I gives a summary sheet of results, which is typical for a single test series for one steel. This summary sheet gives some idea of the large amount of data involved in fatigue testing. In the Joint Investigation of the Fatigue of Metals some dozen different steels have been tested and for each steel there usually have been several series of tests for different heat treatments, different mechanical treatments, etc. In Table I each value given represents the average of not less than six test results.

TABLE I.—TYPICAL TEST RESULTS FOR A SINGLE HEAT TREATMENT OF ONE KIND OF STEEL.

Steel No. 7: 3.5-per-cent Nickel Steel, Heat Treatment "A."

Chemical Analysis of Steel: Carbon, 0.41 per cent; Chromium, 0.18 per cent; Nickel, 3.41 per cent; Silicon, 0.25 per cent; Manganese, 0.75 per cent; Phosphorus, 0.02 per cent; Sulfur, 0.02 per cent.

Heat Treatment: Heat to 1525° F., cool in furnace, reheat to 1525° F., quench in oil, reheat to 1112° F., hold at that temperature, cool in furnace.

Static Tests.—Tension:		Proportional elastic limit	102 000 lb. per sq. in.
		Yield point	107 900 " "
		Ultimate tensile strength	120 800 " "
		Elongation in 2 in	22.6 per cent
		Reduction of area	59.2 "
	Compression:	Proportional elastic limit	102 200 lb. per sq. in.
		Yield point	109 700 " "
	Torsion:	(solid specimen)	
		Proportional elastic limit	64 200 lb. per sq. in.
		Yield point	74 500 " "
	Hardness:	Brinell hardness number	246
		Scleroscope number	29.9
Charpy Impact Tests.—Bending			36.2 ft-lb.
	Tension		186.4 "
		Reduction of area	56.5 per cent
		Elongation in 1 in. (specimen ¼-in. diameter)	20.7 "
Repeated Impact Test.—(Illinois machine)			590 double blows (393 ft-lb.)

ENDURANCE LIMITS.

Repeated-Stress Tests.—	
Rotating-beam (Farmer) test	65 000 lb. per sq. in.
Tension Bending Tests: Stress-ratio for cycle −0.80	not made as yet
" " " " −0.66	66 000 lb. per sq. in.
" " " " −0.40	82 500 " "
" " " " 0	99 000 " "
" " " " +0.29	100 000 " "
" " " " +0.50	not made as yet
Reversed bending (Upton-Lewis)	53 000 lb. per sq. in.
Reversed torsion (Illinois machine)	35 000 lb. per sq. in.
Reversed torsion (Olsen-Foster)	not made as yet.
Direct tension-compression	not made as yet.

THE "ENDURANCE LIMIT" AND THE EXPERIMENTAL EVIDENCE FOR ITS EXISTENCE.

A question of prime importance in connection with any study of the failure of metals under repeated stress is the question of the existence of a limiting stress, called the endurance limit," below which fracture will not occur no matter how many times the stress is repeated.

From the time of Wöhler, who made the first extensive investigation of the strength of metals under repeated stress, it has been customary in studying the results of a series of repeated-stress tests to use a graph in which values of unit stress are plotted as one coordinate and values of some function of the number of repetitions necessary to cause failure are plotted as the other coordinate. A convenient designation for such a diagram is an $S-N$ diagram, and that term will be used in this paper. $S-N$ diagrams may be plotted to various systems of coordinates, ordinary (Cartesian), logarithmic, semi-logarithmic, etc.

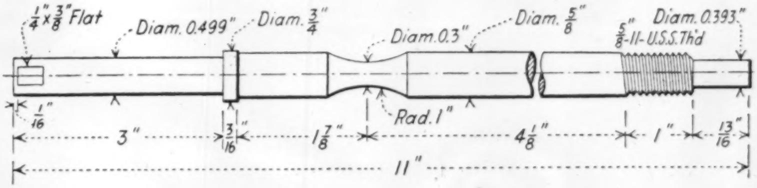

FIG. 8.—Specimen for Tests Under Steady Tension Combined with Reversed Bending.

While it is not feasible to present in such a paper as this anything like a complete tabulation of available data on repeated stress tests, the writers, having studied a considerable amount of such data, both for tests made under their personal observation and for tests made by others, present graphs of test data for four series of tests which they believe to be typical. It will be noted that the four series of tests chosen are from four different laboratories.[1]

Fig. 11 shows the $S-N$ diagrams for the chosen series of tests plotted to ordinary (Cartesian) coordinates, Fig. 12 shows the $S-N$

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[1] 1. Wöhler's tests. See *Engineering* (London), Vol. XI (1871).

2. Tests at Watertown Arsenal. See *Tests of Metals*, 1888 to 1895 and 1890 to 1909.

3. Tests by McAdam at the U. S. Naval Engineering Experiment Station, Annapolis, Md. See *Chemical and Metallurgical Engineering*, December 14, 1921. These tests are spoken of as the "Annapolis" tests.

4. Tests at the University of Illinois Engineering Experiment Station made in the progress of the Joint Investigation of the Fatigue of Metals, under the auspices of the National Research Council, Engineering Foundation, the General Electric Co., and the University of Illinois. These tests are spoken of as the "Joint Investigation" tests.

diagrams plotted to semi-logarithmic coordinates, and Fig. 13 shows them plotted to logarithmic coordinates.

These diagrams, together with diagrams of other tests, seem to the writers to offer two items of evidence in favor of the existence of an endurance limit:

1. However they are plotted, the $S-N$ diagrams all become either horizontal or very nearly so as the value of N is increased into the millions. In interpreting the results of the Annapolis tests the experimenter judged that the $S-N$ diagram did not become horizontal, but that its slope was so slight that a reduction of unit stress of 15 per cent increased the value of N 1000 times. Even for such parts as steam turbines the practical difference between considering the $S-N$ diagram horizontal, and considering it slightly sloping, is small as regards the effect on allowable working stresses.

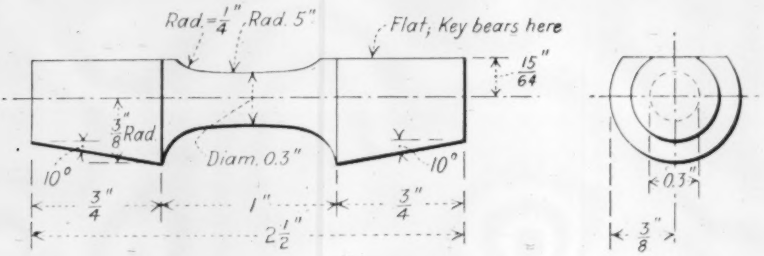

FIG. 9.—Specimen for Reversed Torsion Tests.

2. In the $S-N$ diagrams there is a distinct "break" in the diagram at the point where the diagram becomes horizontal, or nearly so. This break is shown most clearly by the diagrams plotted to ordinary coordinates, Fig. 11, but it is evident in Fig. 12 and Fig. 13 as well, except possibly for the Annapolis results.[1]

3. Another item of evidence in favor of the existence of an endurance limit is the rise of temperature which is noted under repeated stress if the unit stress is above that corresponding to the break of the $S-N$ diagram. This is shown in Fig. 14, which shows typical results. In the left-hand half of Fig. 14 is plotted an $S-N$ diagram to logarithmic coordinates, while in the right-hand half is plotted a diagram with unit stress as ordinates and rise of temperature after 1000 rapid reversals of stress as abscissas. This thermal indication of an endur-

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[1] In the Annapolis tests there were very few specimens broken under high stresses. The test data were, for the most part, obtained at stresses not much above those for the horizontal part of the curve. There were few tests in the region where the "break" would probably occur. It should also be noted that test results from specimens which were not broken after a test do not locate points *on* the $S-N$ diagram, but rather points *on* or *below* that diagram.

ance limit was studied by Stromeyer, and later by Gough.[1] It is discussed quite fully in *Bulletin No. 124* of the Engineering Experiment Station of the University of Illinois, which is a progress report of the Joint Investigation of the Fatigue of Metals. This thermal limit is found to coincide closely with the stress at the horizontal part of the $S-N$ diagram. It may be added that tests at Illinois made since the appearance of *Bulletin No. 124* give additional confirmation of this coincidence.

So far as the writers can determine there is no experimental evidence which tends to discredit the existence of an endurance limit. Some writers have proposed formulas for repeated stress which would imply that such a limit did not exist and that any stress, however low, will, if repeated often enough, fracture any material. These writers stated, however, that such formulas were given as *safe* formulas to use, in the absence of any body of test data for tests extending to tens of millions of repetitions of stress, rather than as formulas based on adequate test data.

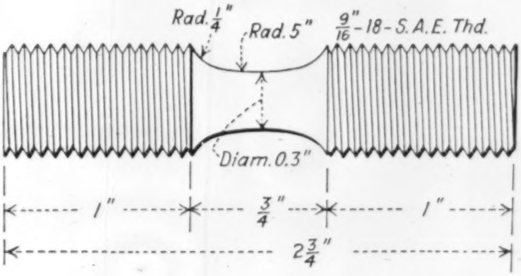

FIG. 10.—Specimen for Tests Under Reversed Axial Stress (Tension-Compression).

It can hardly be stated dogmatically that there exists for a ferrous metal an endurance limit below which the metal will stand an *infinite* number of repetitions of stress, but in view of the three items of experimental evidence given in the preceding paragraphs it is believed that there exists for a ferrous metal a limiting stress, which may be designated as the endurance limit (or fatigue limit) and which even for the extreme cases of members for high-speed machinery may be regarded as a limit of the strength of the material under repeated stress.

Whether for non-ferrous metals there exist endurance limits as well defined as those for ferrous metals is a matter not yet determined.

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[1] Stromeyer, "Memorandum of the Chief Engineer of the Manchester (England) Steam Users Association," 1913.

Gough, *The Engineer* (London), August 12, 1921.

From the shape of $S-N$ diagrams for ferrous metals it may be seen that results from tests made by subjecting specimens to a given high stress and noting the value of N for the different specimens cannot be compared with the results of tests made to determine the endurance limit. As an illustration consider the test results given in Fig. 15. If a comparison of the values of N for a stress of 60,000 lb. per sq. in. were made the cold-drawn steel would appear to be the

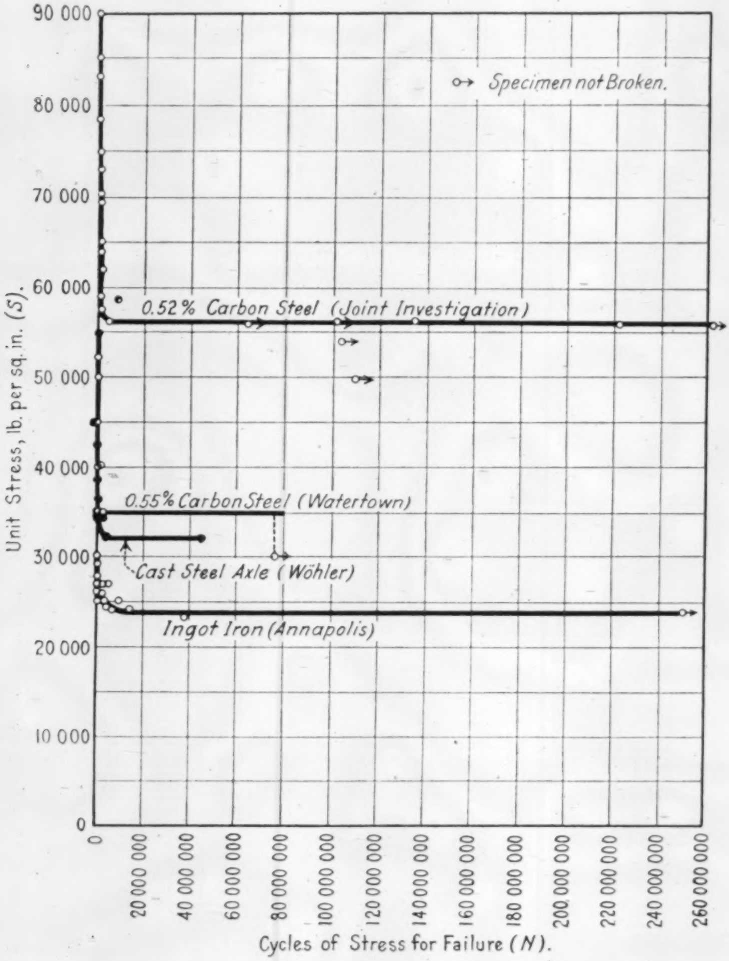

FIG. 11.—Cartesiar $S-N$ Diagrams for Reversed-Stress Tests.

better metal; if a comparison of the values of N for a stress of 45,000 lb. per sq. in. or a comparison of the endurance limits is made, the 1.20-per-cent carbon steel appears to be the better metal.

Various forms of repeated-impact testing machine (such as the "Stanton" machine and the machine shown in Fig. 6) give comparisons of values of N for different specimens subjected to blows of a constant amount of energy. The specimens are notched or grooved to hasten fracture, and the localized stress at the notch or groove is high and cannot be determined accurately. Results obtained by the use of such repeated-impact machines may have a high value in detecting

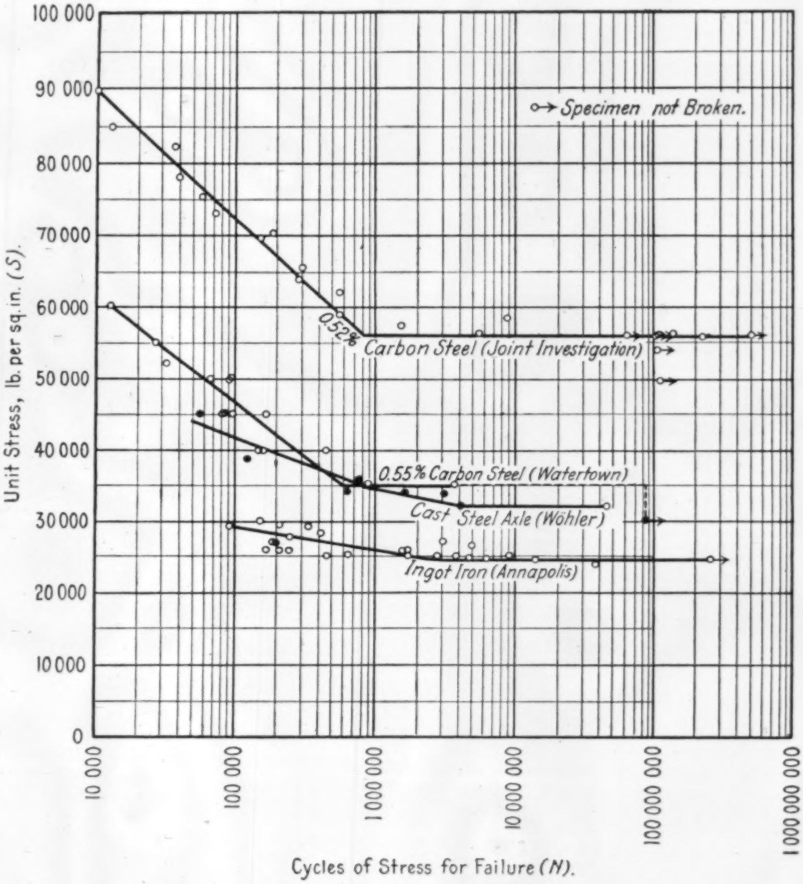

FIG. 12.—Semi-Logarithmic $S-N$ Diagrams for Reversed-Stress Tests.

material with faulty heat treatment, or in picking out material which shall be highly resistant to occasional heavy overload,[1] but the results obtained by the use of such machines do not give values which can be used to indicate limiting stresses for material to be subjected to millions of repetitions of a given working stress.

THE SIGNIFICANCE OF THE RESULTS OF REPEATED-STRESS TESTS.

The designer and the user of metal parts of machines and structures has to consider the possibility of failure in any one of three ways (or by combinations of these three ways): (1) static failure, (2) failure by impact, and (3) failure by progressive fracture under repeated stress.

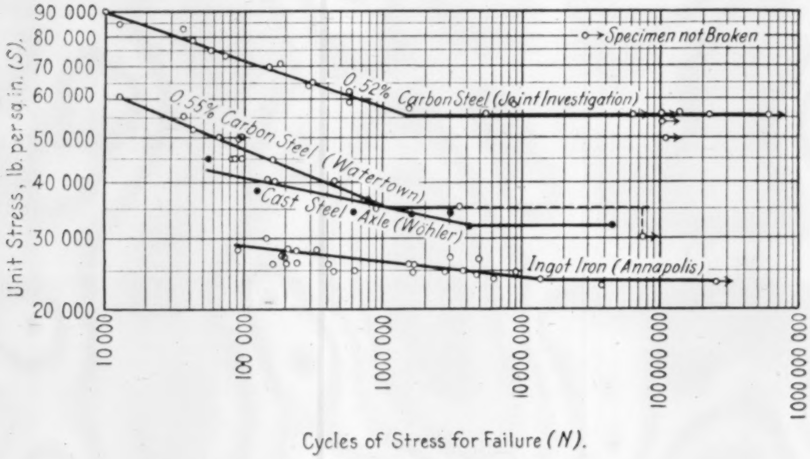

FIG. 13.—Logarithmic $S-N$ Diagrams for Reversed-Stress Tests.

The formulas of the mechanics of materials which are in common use by designers are based on the idea of safeguarding against static failure. The ordinary formulas fail to take account of many localized stresses in machine parts and structural members, and the use of those formulas is justified by the fact that such localized stresses do not, in general, cause static failure either by actual rupture or by general distortion of the part. In choosing material to resist static load conditions, the yield point or some "elastic limit" seems to be the best criterion of strength, though the tensile strength serves fairly well.

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[1] The engineer of tests of a well-known firm of automobile manufacturers stated in a letter that the "Stanton" test had been most useful in determining suitable material for automobile parts subjected to hard service.

Even in structures and machines subjected to few repetitions of load it is usually thought well to provide some reserve of tenacity in the material so that severe distortion shall not necessarily be followed by total collapse. This attempted insurance against total collapse is usually provided by using metal which has a good degree of ductility—no designer would think of using a cast-iron chain hook, for example.

Formulas for the design of parts which are to resist impact are not in common use. Such formulas would be very much more complex than the formulas for resistance to static load. In considering the action of a member under impact it is necessary to consider the energy absorbed by every part of the piece, not merely the action at some critical section. If some slight distortion is permissible in the part, the ductility of the material is a factor to be considered. The significance of impact tests, and of impact in general, is the subject of a symposium at this meeting of the Society and need not be discussed here at length. It may be noted in passing that the significance of tests made by fracturing a notched specimen by means of a single violent blow from a swinging pendulum is not a matter regarding which there is unanimity of opinion among testing engineers.

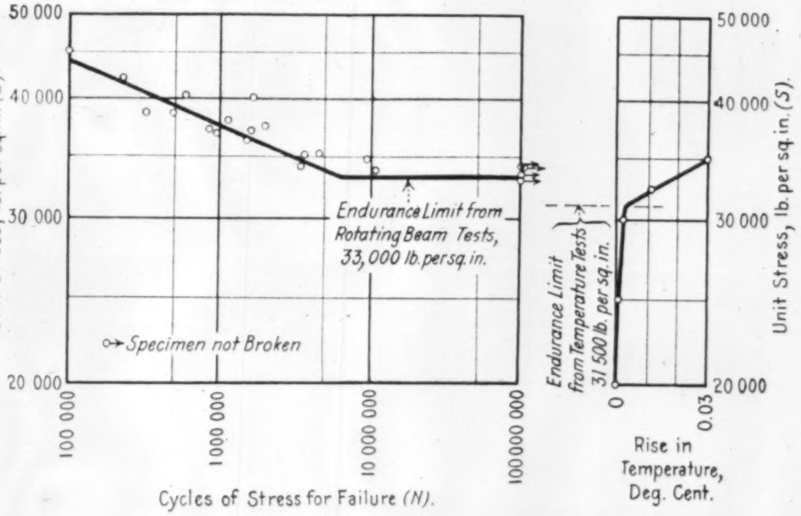

FIG. 14.—Test Results for Rotating-Beam Test and for Thermal Test.

A fatigue failure seems to be a progressive failure, which begins with localized structural damage affecting only a minute portion of a machine part or a structural member. This damage is of such slight extent that it produces very little distortion of the member as a whole—hardly enough to be detected even by extensometer measurements for a single cycle of stress. In some experiments by Bairstow at the British National Physical Laboratory repeated-stress tests were made using, at intervals, an extensometer sensitive to 0.000002 in. For some tests in which the cumulative action of repeated stress finally caused failure, the extensometer gave no warning that deterioration was going on in the specimen.

In considering the action of machine parts under repeated stress the designer must consider many localized stresses which he was justified in neglecting in members subjected to static load conditions. Some of these localized stresses he can compute by the more elaborate formulas of the mathematical theory of elasticity, some he cannot compute, and these he must seek to minimize by the use of generous fillets, the avoidance of reëntrant angles in outline, and the providing of generous bearing surfaces. In choosing suitable material for such members it is believed that, for ferrous metals at least, the endurance limit furnishes the best criterion of resistance to repeated stress, with the ultimate tensile strength or the Brinell hardness (which seems to be related to ultimate strength) as a somewhat less reliable index.

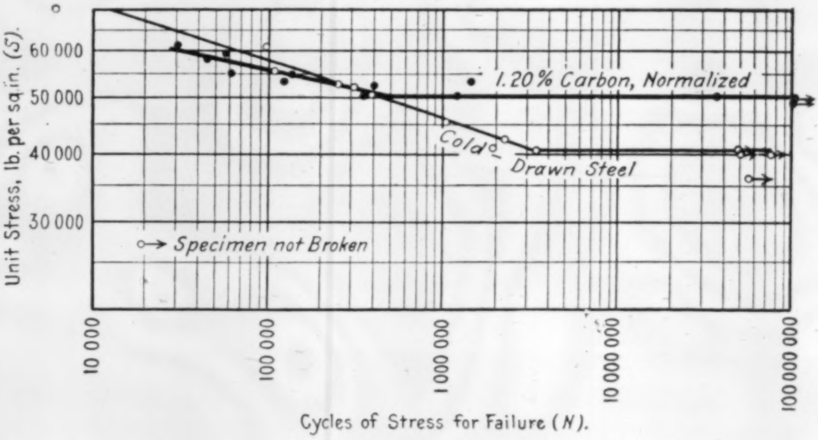

FIG. 15.—Test Results for Cold-Drawn Steel and 1.20-per-cent Carbon Steel.

To some materials engineers the idea that the tensile strength of a metal is a better index of its resistance to repeated stress than is its elastic limit may come as somewhat of a shock. Viewed under the microscope, fatigue failure is seen to be not a flow of the material, such as that which occurs at the elastic limit, but an actual sliding or tearing apart of parts of the material. Over some microscopic area the metal seems to reach its ultimate strength, and thus actual fracture spreads. Fatigue failure seems to be really a phenomenon of actual rupture rather than of elastic flow and distortion of crystallin grains.

It is believed, however, that the most reliable determination for strength to resist oft-repeated stress of a known magnitude consists in a series of tests of specimens which are subjected to repetitions of various stresses. It is usually convenient to begin such a series by using rather high stress and consequent short endurance, then step by step to diminish the stress until the endurance attained indicates that the endurance limit has been reached. Usually this can best be determined by means of an $S-N$ diagram. It is believed that there are great possibilities of usefulness in the "rise-of-temperature" test, especially as a check test or a preliminary indicator for the endurance limit.

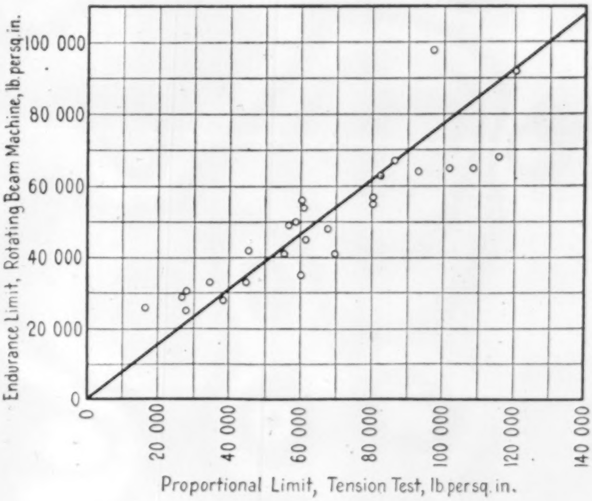

FIG. 16.—Correlation of Endurance Limit with Proportional Limit.

Rarely is it possible to classify with exactness the service to which a machine part is to be subjected. Usually there must be considered the danger of static failure under the working load, the danger of fatigue failure under repetition of load (especially at points of localized stress), and the danger from occasional shocks and accidental heavy overloads. In general, no single formula will serve the designer of a machine part, and no single physical property will serve the engineer who selects the material of which it is to be made.

RECENT RESULTS FROM REPEATED-STRESS TESTS.

Since the publication of *Bulletin No. 124* of the Engineering Experiment Station of the University of Illinois, the work of the Joint Investigation of the Fatigue of Metals has been in progress, and one or two features of that progress may be noted here.

Figs. 16-20 inclusive show the relations found between the endurance for various steels and various other physical properties. It is believed that these diagrams are self-explanatory.

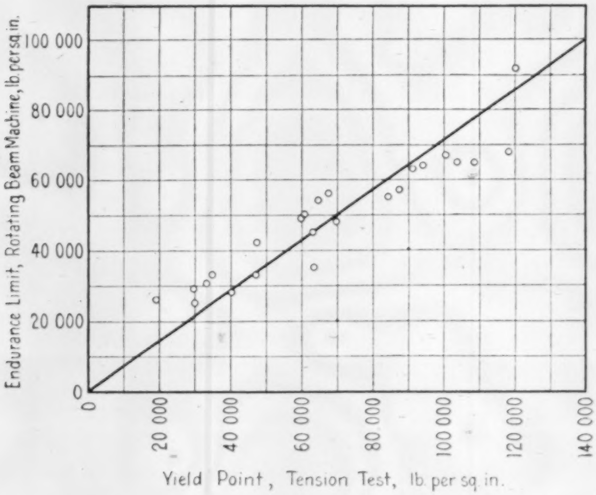

FIG. 17.—Correlation of Endurance Limit with Yield Point.

A brief study of the effect of speed of machine on the value obtained for the endurance limit has been made using two different steels. Using "Farmer" machines, tests were run at 200 r.p.m., and other tests were run at 5000 r.p.m. The endurance limit as determined from these tests differed but little from the endurance limit previously found for the same steels with the machines running at 1500 r.p.m.

A study of the effect of varying heat treatments on the endurance limit of three different steels is being made, and while the tests have not been completed one basic open-hearth steel with a carbon content of 0.49 per cent gives results indicating that "drawing" the oil-quenched steel at a temperature as high as 600° F. did not reduce the endurance limit appreciably, although the tensile strength and the Brinell hardness were slightly reduced. It may be that the weakening effect of drawing the temper was offset by the relief from internal stresses set up in quenching.

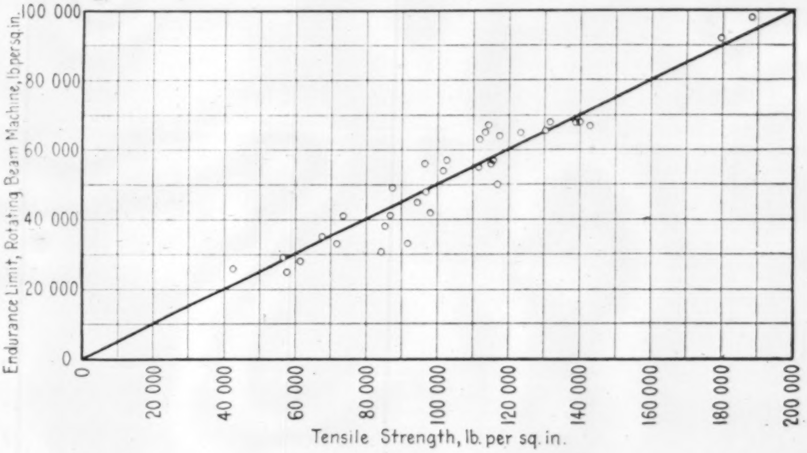

FIG. 18.—Correlation of Endurance Limit with Tensile Strength.

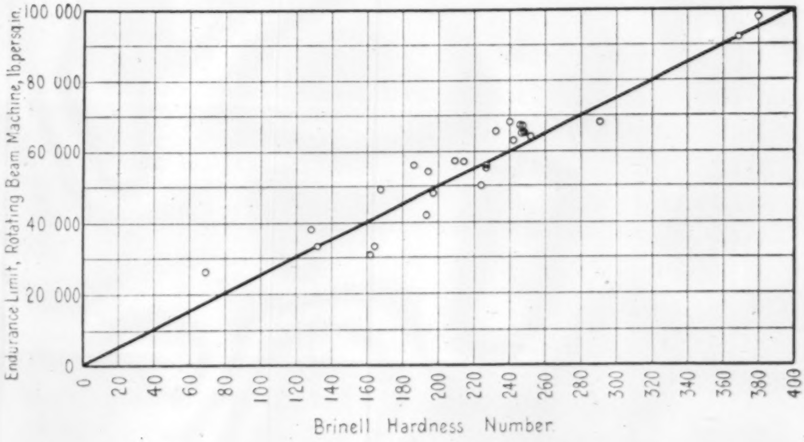

FIG. 19.—Correlation of Endurance Limit with Brinell Hardness.

A study of the endurance limit with stresses not completely reversed is in progress, using the machine shown in Fig. 2. Here only a few results have been obtained. The method in most general use for estimating the relative severity of complete reversals of stress and partial reversals of stress is one developed by Goodman, and independently by J. B. Johnson. Following their analyses it would seem that if S_r is the endurance limit under complete reversal of stress, the endurance limit for the same material subjected to cycles of stress varying from 0 to a maximum will be 1.5 S_r. Fig. 21 is a diagram showing values obtained by using the Goodman analysis. The results so far obtained in the tests at Illinois fall close to the curve of Fig. 21.

If in the tests already made it is attempted to use unit stresses higher than the yield point of the material, failure takes place, and the failure is usually not a fatigue failure with a sharp fracture across the specimen, but a failure by excessive bending of the specimen—such a failure as occurs in a "static" bending test without the opening up of a crack. It would seem that in no case should the strength of the metal be regarded as higher than the yield point as determined by a static test.

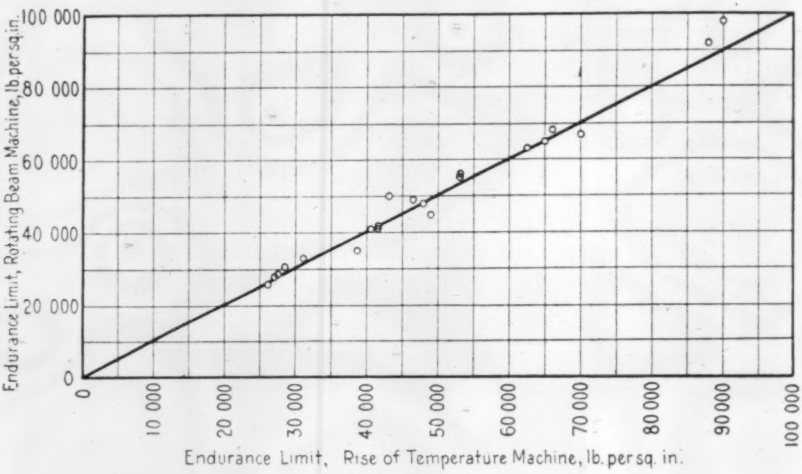

Fig. 20.—Correlation of Endurance Limit by Bending Test to Failure with Endurance Limit by Rise of Temperature.

An interesting series of tests is now in progress. Specimens which have withstood 100,000,000 reversals of a stress close to the endurance limit have been subjected to further reversals at slightly higher stresses—in one case 16 per cent higher—and they have withstood without failure a second run of 100,000,000 reversals of this increased stress. Static tension tests on other specimens which have withstood 100,000,000 reversals of stress close to the endurance limit have given distinctly higher values for tensile strength than those given by tension tests of the material before repeated stressing. These tests are by no means complete, but the possibility that steel may be actually benefited by repeated stressing below the endurance limit is of interest.

Among the numerous lines of possible investigation of the phenomena of repeated stress, two seem to the writers to be worthy of special attention: (1) the extension of investigations of the fatigue strength of non-ferrous metals, with an attempt to see whether they show any phenomena markedly different from those shown by ferrous metals; and (2) an investigation of the strength of steel under repeated stress and at high temperature. There is almost a complete dearth of test data on this second item, and the problem is certainly one of great importance to makers and users of steam turbines and internal combustion engines.

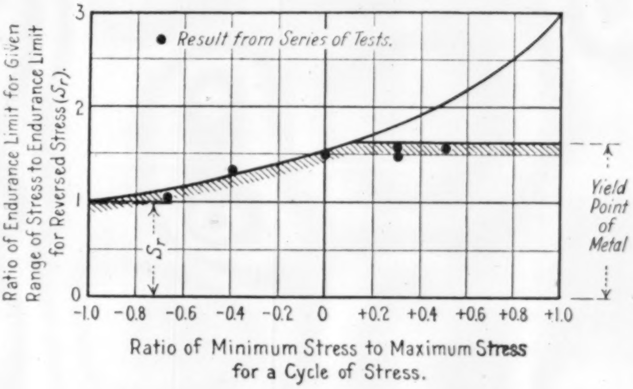

FIG. 21.—Effect of Range of Stress on Endurance Limit.

DISCUSSION.

Mr. McAdam. MR. D. J. MCADAM, JR. (*presented in written form*).—It may be of interest to compare the results obtained by the joint investigation with a series of numerous experiments made at the same time by means of a different type of machine and specimen.

For several years, experiments on endurance of steel under repeated stresses have been in progress at the U. S. Naval Engineering Experiment Station. These experiments were made on a great variety of carbon and alloy steels. Results of some of the experiments were published in the article referred to by the authors.

Most of the experiments were made on a machine of the rotating cantilever type. The specimen used was tapered so that the stress was uniform, within about 1½ per cent, over 1½ in. of its length, and so that the plane of maximum stress was ¾ in. out from the fillet.

TABLE I.—AVERAGE RESULTS OF CHEMICAL ANALYSIS.

Material.	Carbon, per cent.	Manganese, per cent.	Phosphorus, per cent.	Sulfur, per cent.	Silicon, per cent.	Nickel, per cent.
O-2, O-3, O-4, O-5, O-6, O-7	0.24	0.44	0.047	0.032	0.015	....
Q-3........	0.24	0.64	0.009	0.031	0.18	3.34

In comparing the results of these experiments with those of the joint investigation it will be noted that the results obtained in the two laboratories do not differ greatly in their practical applicability to the design of machinery. The apparent differences between the two sets of results have been magnified by differences in the methods of summarizing and illustrating results, and in the statement of conclusions.

It is true, as stated by the authors in the note at the bottom of page 276, that in the Annapolis tests as previously reported there were comparatively few specimens broken at stresses high enough to cause failure after only a few thousand cycles. Most of the specimens endured more than a million cycles and very few broke at less than 100,000 cycles. Since the Annapolis results were published, however, additional experiments have been made including a number at stresses sufficient to cause failure at less than 100,000 cycles.

These recent experiments have led to a series of results so uniform that, in drawing graphs to illustrate the results, the personal

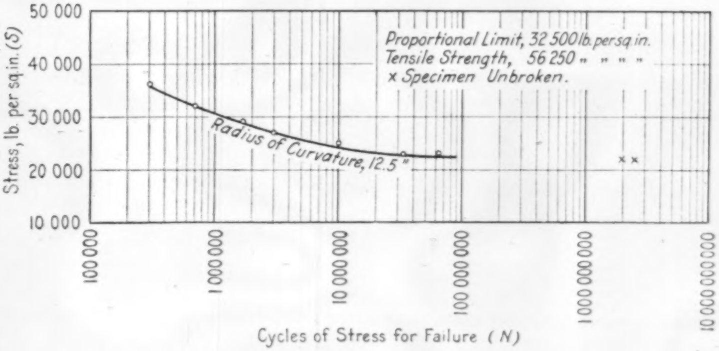

FIG. 1.—Semi-Logarithmic S-N Diagram for Carbon Steel, Material O-5.
The radius of curvature indicated is that of the original drawing of which the figure shown is a reproduction about one-third size.

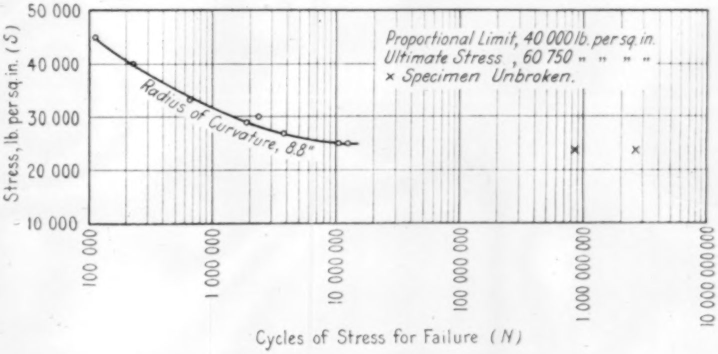

FIG. 2.—Semi-Logarithmic S-N Diagram for Carbon Steel, Material O-6.
The radius of curvature indicated is that of the original drawing of which the figure shown is a reproduction about one-third size.

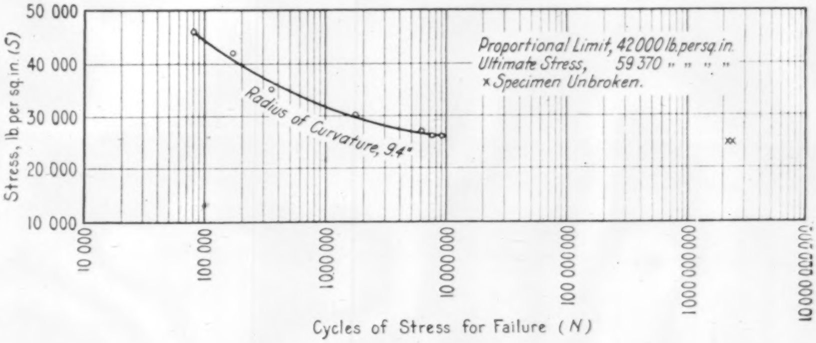

FIG. 3.—Semi-Logarithmic S-N Diagram for Carbon Steel, Material O-4.
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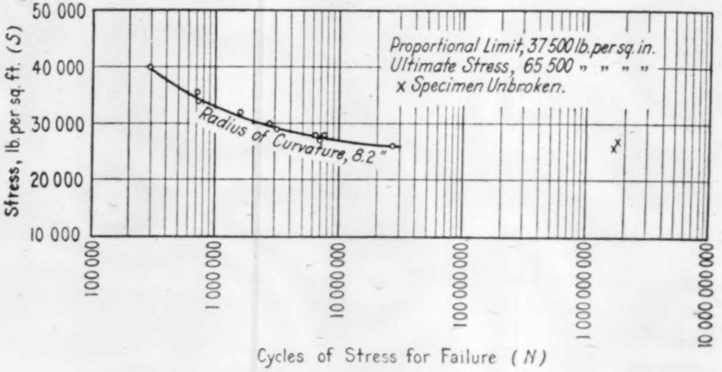

FIG. 4.—Semi-Logarithmic *S-N* Diagram for Carbon Steel, Material O-3.

The radius of curvature indicated is that of the original drawing of which the figure shown is a reproduction about one-third size.

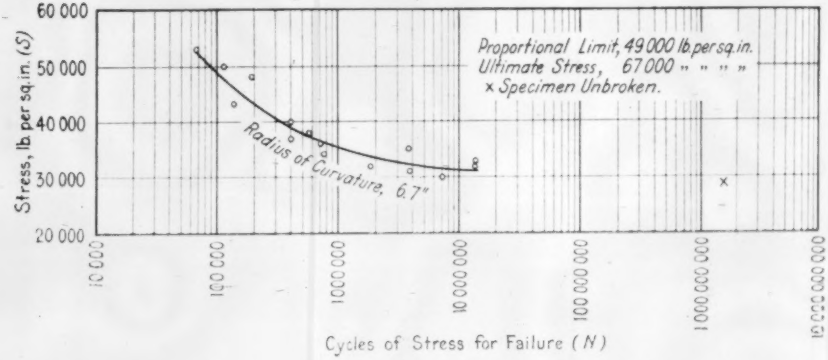

FIG. 5.—Semi-Logarithmic *S-N* Diagram for Carbon Steel, Material O-2.

The radius of curvature indicated is that of the original drawing of which the figure shown is a reproduction about one-third size.

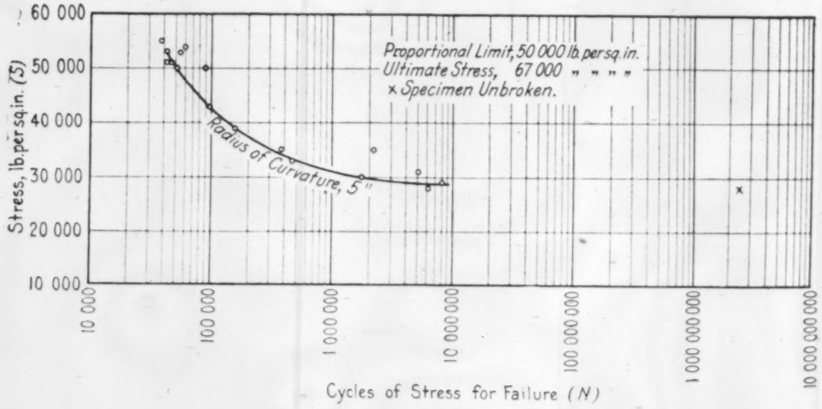

FIG. 6.—Semi-Logarithmic *S-N* Diagram for Carbon Steel, Material O-7.

The radius of curvature indicated is that of the original drawing of which the figure shown is a reproduction about one-third size.

Mr.McAdam. equation is only a small factor. The results of some of the experiments are illustrated by Figs. 1 to 7, inclusive. In these graphs semi-logarithmic plotting has been used. It is believed that this method of plotting is preferable to the logarithmic method of plotting used in the first published report by the joint investigation.

Figs. 1 to 6, inclusive, illustrate results obtained with carbon steel, having about 0.23 per cent of carbon, heat-treated in various ways. Fig. 7 illustrates results obtained with a nickel steel. The chemical composition of each of these two steels is given in Table I. The heat treatments, given to the material in the form of $1\frac{1}{4}$-in. round bars, are listed in Table II. The tension test results are given in Table III.

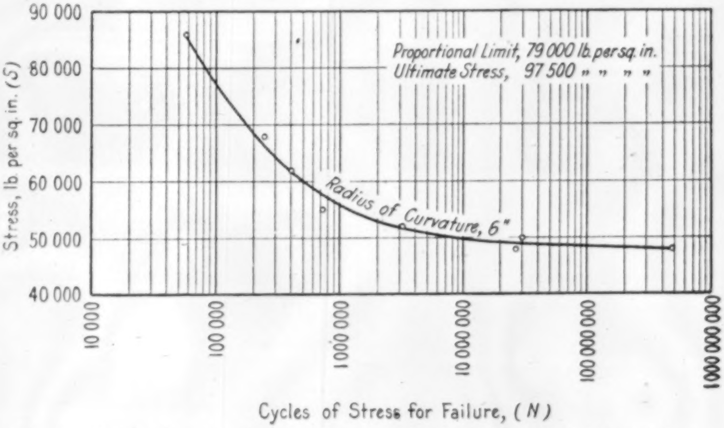

FIG. 7.—Semi-Logarithmic *S-N* Diagram for Nickel Steel, Material Q-3.

The radius of curvature indicated is that of the original drawing of which the figure shown is a reproduction about one-third size.

These recent experiments have shown that in some steels the slope of the *S-N* diagram becomes decidedly greater as the stress is increased above the point necessary to cause fracture at about 100,000 cycles. The experiments have also shown conclusively that in these steels there is no "break" in the *S-N* diagram. There is evidently continuous curvature as the stress decreases until the diagram becomes practically a straight line with slight downward slope.

The stress range of the upper part of the diagram is greater, the greater the elastic ratio of the steel. The curvature, in the upper part of the diagram at least, varies with the composition and heat treatment of the material. Since drawing these curves, it has been noticed that the upper part of each diagram corresponds rather closely to an arc of a circle. The radius of curvature varies with the

Mr. McAdam. heat treatment and probably also with the chemical composition. It will be noted that the radius of curvature of the graph of annealed carbon steel, Fig. 1, is the greatest. As illustrated by Figs. 2 to 6, inclusive, the radius of curvature evidently decreases as the drawing temperature is lowered. Fig. 7 seems to indicate that for nickel steel, the radius of curvature is less than for carbon steel that has been drawn at the same temperature.

TABLE II.

MATERIAL.	HEAT TREATMENT.
O-2	Heated to 1600° F., held 30 min., cooled in oil, reheated to 900° F., held 30 min., cooled in furnace.
O-3	Heated to 1600° F., held 30 min., cooled in oil, reheated to 1100° F., held 30 min., cooled in furnace.
O-4	Heated to 1600° F, held 30 min., cooled in oil, reheated to 1300° F., held 30 min., cooled in furnace.
O-5	Heated to 1600° F., held 30 min., cooled in furnace.
O-6	Heated to 1600° F., held 30 min., cooled in air.
O-7	Heated to 1600° F., held 30 min., cooled in oil, reheated to 700° F., held 30 min., cooled in furnace.
Q-3	Heated to 1475° F., held 30 min., quenched in oil, reheated to 1200° F., held 30 min., cooled in furnace.

It is possible also that the curvature and slope of the lower part of the diagram vary with the composition and heat treatment of the steel. To draw conclusions in regard to this, however, it would be necessary to have results of many more experiments at such stresses that the specimens endure many million cycles before fracture.

TABLE III.—TENSION TEST RESULTS.

Averages of all determinations for each material.

Material.	Tensile Strength, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.
O-2	67 000	49 000	47 000	37.0	68.8
O-3	65 500	37 500	42 250	38.5	69.5
O-4	59 370	42 000	40 120	41.7	72.8
O-5	56 250	32 500	36 000	39.0	60.5
O-6	60 750	40 000	42 000	39.0	63.0
O-7	67 000	50 000	50 000	37.5	68.5
Q-3	97 500	79 000	80 000	26.0	67.5

Though the slope of the lower part of the diagram, for steels at least, is evidently slight, the writer does not believe that the evidence at present indicates that the diagram becomes horizontal.

The writer believes that the authors in a desire to emphasize the fact that the slope of the lower part of the diagram is slight, have unintentionally so drawn their diagrams as to over-emphasize the so-called "break." Their diagrams in Figs. 12, 13 and 14, if drawn as

Mr. McAdam.

curves instead of in the form of two intersecting lines (in some cases intersecting at a point well below the region indicated by actual experiments), would be more in accordance with experimental results.

The writer wishes to emphasize the great value of the work done by the joint investigation. Whether or not the existence of any absolute endurance limit has been established, this investigation has resulted in much valuable data that may be used in calculating practical endurance limits. Such limits depend somewhat on the service that the metal is to endure.

In the publication of the Annapolis results, a series of practical endurance limits are given, based on the stresses which the various kinds of material will endure for one hundred million cycles. The values thus calculated do not differ greatly from the values obtained with similar material by the joint investigation.

It may be of interest to state that we have run some experiments on an impact machine of the Stanton type. If the energy per blow is plotted as ordinate, and the number of blows is plotted as abscissa on logarithmic paper we find that the diagram is practically a straight line with steep downward slope from the position representing a single blow to a point representing about 100,000 blows. At about this point the line begins to curve gradually until the slope becomes slight.

Mr. Tuckerman.

MR. L. B. TUCKERMAN (*presented in written form*).—A comparison of the reports of the two sets of experiments on fatigue of metals by Moore[1] and McAdam[2] raises two principal questions because of the divergent conclusions drawn.

1. Are the two methods of experimentation equivalent or is there some unknown factor which makes it impossible to compare the experimental results in the two investigations?

2. Is the "Endurance Limit" in Moore's report a valid conclusion from his data?

In an attempt to answer the first question a search was made through the results of both for material tested in both investigations which could safely be considered identical or at least reasonably comparable. The best material for such a comparison seemed to be the samples of American Ingot Iron. The materials used in the two investigations were as near identical in chemical composition and physical properties as could be reasonably expected from two different shipments of material. In both cases, 26 specimens were tested

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[1] H. F. Moore and J. B. Kommers, "An Investigation of the Fatigue of Metals," *Bulletin*, University of Illinois, Vol. 19, No. 8, October 24, 1921. *Bulletin No. 124*, Engineering Experiment Station.

[2] D. J. McAdam, Jr., "Endurance of Steel under Repeated Stresses," *Chemical and Metallurgical Engineering*, Vol. 25, No. 24, pp. 1081–1087, December 14, 1921.

Mr. Tuckerman. so that the difference in the test machines and type of specimen was the only outstanding difference. The comparison of chemical analysis and physical properties is given in Table IV. As will be seen, the chemical composition, ultimate strength, elongation and reduction of area are remarkably alike for material not known to be from the same heat and rolling. The differences in proportional limit, yield point, Brinell hardness and Shore scleroscope readings are not thought to be significant in view of the uncertainty involved in their determination.

In Fig. 8 are plotted on a log stress - log cycles to fracture scale, the results of the two series of fatigue tests on this material, with standard finish, and also Moore's results on a "smooth turned" finish. From the description of the finish in the two reports, it would seem that if there was any difference the standard finish used by McAdam was the smoother of the two standard finishes. In the results of the fatigue tests, however, practically half of McAdam's specimens failed at stresses below the lowest stress at which Moore reported failure with his standard finish. The discrepancy of the results is obvious. But when Moore's "smooth turned" results are plotted on the same diagram, there is substantial agreement with McAdam's results so far as can be judged for such widely scattering points.

TABLE IV.—COMPARISON OF CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF AMERICAN INGOT IRON TESTED BY MOORE AND MCADAM.

Observer.	Carbon, per cent.	Chromium, per cent.	Nickel, per cent.	Silicon, per cent.	Manganese, per cent.	Phosphorus, per cent.	Sulfur, per cent.	Heat Treatment.
Moore....	0.02	.....	.....	0.02	0.03	0.005	0.042	as received
McAdam..	0.023	.....	.....	0.005	0.037	0.002	0.031	as received

Observer.	Set.	Proportional Limit, lb. per sq. in.	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.	Reduction of Area, per cent.	Brinell Hardness.	Shore.
Moore....	14 400	16 100	19 000	42 400	48.3	76.2	69	18
McAdam..	.....	20 000	25 000	44 250	48.5	74.5	86.6	11.0

This raises the interesting question whether the "smoothness" of a finish is a sufficient criterion of its fatigue characteristics. Lacking any definite reason for assuming that the cantilever (White-Souther) type of loading should give fatigue results different from two point simple beam (Sondericker-Farmer) type of loading, there is in these results a suggestion that for some reason the fatigue characteristics of McAdam's standard finish approached more nearly those of Moore's "smooth turned" than of Moore's standard finish. Is it

Mr. Tuckerman.

possible that the fatigue characteristics of a finish are a function not only of the "smoothness" of the finish but of the manner of approach to that finish? It seems not unreasonable to suppose that the effects of a roughing cut may extend some distance into the material, so that a finish approached by a few heavy roughing cuts might have different fatigue characteristics than an apparently similar finish approached by a larger number of light roughing cuts. If that were the case, it is conceivable that machine shop practice, uniform in each laboratory but differing in the two laboratories, might account for the consistency of results at each laboratory and the apparent discrepancy of the results of the two. A conclusive answer to these questions could only be made as a result of further experimentation. Such further experimentation might take the form of a series of tests on alternate specimens cut from the same material, *machined*, *finished* and *tested* at the two different laboratories, in accordance with their previous machine shop practice, compared with tests on the same material machined with different depths of roughing cuts.

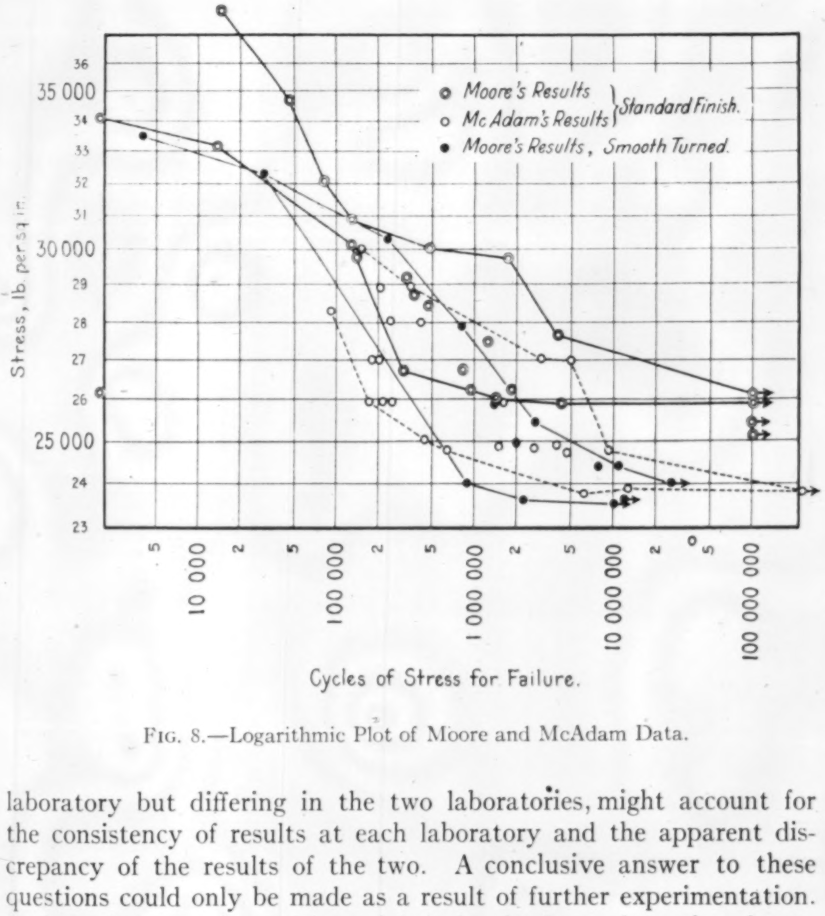

FIG. 8.—Logarithmic Plot of Moore and McAdam Data.

Mr. Tuckerman.

Moore's test results are interpreted by him to indicate an abrupt discontinuity in the slope of the stress-reversals diagram at a certain stress called the "endurance limit." At this point he infers that the curve changes into a horizontal straight line. In order to bring this change out clearly he plots the results on a log stress - log cycles to failure scale. The question arises whether the abrupt change of slope of the curve may not be fictitious, the appearance being due to the type of plotting he has chosen. In an attempt to answer this question we make use of the following fact: A discontinuity of slope in any curve remains a discontinuity of slope in any analytic deformation of the curve which is continuous at the point of slope discontinuity. If then from a series of experimental data a curve ABC (Fig. 9) is inferred having an apparent discontinuity at B, it may be questioned whether a continuous curve $A'B'C'$ did not equally well represent the data. As an aid to answering this question the data may be plotted on another scale with no discontinuity at B deforming AB into some such form as $A''B''$ preferably of reversed curvature. If the data on this new scale do not suggest a discontinuity at B'' such as $A''B''C''$ but rather suggest a continuous curve $A''B''C'''$ more doubt is thrown on the reality of the discontinuity at B inferred from ABC. If, however, the distorted plotting with reversed curvature, which would have at least partially straightened out any smooth curve such as $A'B'C'$ still suggests a discontinuity at B'', the reality of such a discontinuity is rendered more probable. Reasoning in this way I have replotted Moore's data for Steel No. 6 on a log stress - log cycles to fracture scale, choosing the zero of the log cycles to fracture at log 10,000 so as to produce a marked curvature of the lower points (Fig. 10). Examination of these curves shows that the sudden break in slope is if anything more clearly indicated in these curves than in Moore's plots.

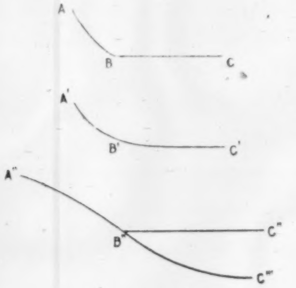

FIG. 9.

Mr. Tuckerman.

So far as these curves show, the "endurance limit" is clearly indicated by Moore's results. In view, however, of the scattering of the observed points which seems inherent in fatigue testing, the results would be more conclusive if a larger number of tests had been run to the arbitrary limit of 100,000,000 reversals including a number run at stresses well below the "endurance limit".

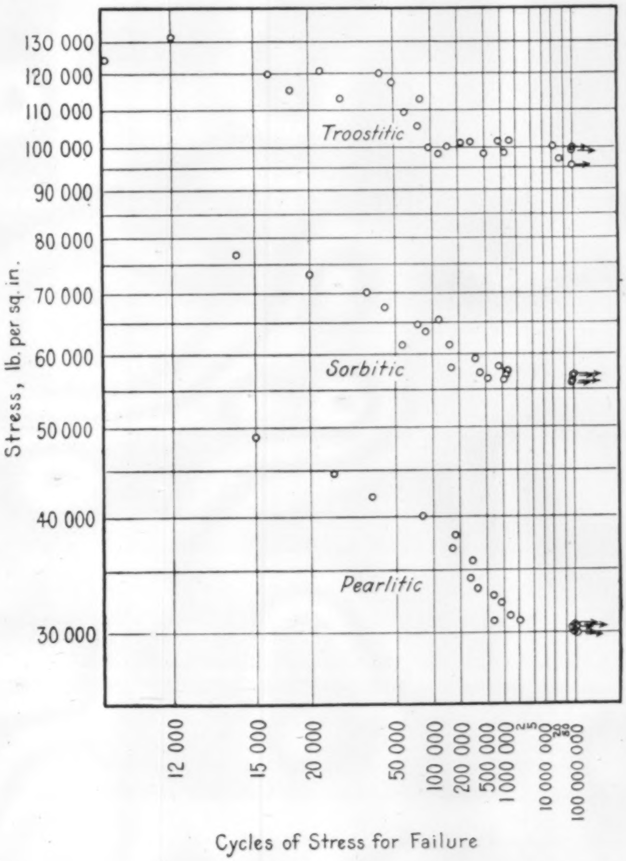

FIG. 10.—Logarithmic Replot of Moore's Data for Steel No. 6, 0.93 C.

That this "endurance" limit actually represents a stress below which failure would not occur even after an indefinitely large number of repetitions cannot of course be safely inferred from these considerations. An extrapolation of observed results beyond the limits of existing data is always unsafe, and in general can only be justified by theoretical considerations which indicate that the phenomena are

Mr. Tuckerman. continuous in the range of extrapolation. There are of course indications of such a continuity in the Strohmeyer[1] effect and in Smith's[2] experiments as confirmed and extended by Gough,[3] but this evidence seems at present insufficient to prove the validity of extrapolation.

Mr. Gillett. MR. H. W. GILLETT (*presented in written form*).—The U. S. Bureau of Mines has in progress at Cornell University a series of endurance tests, made, not with the primary idea of studying the variables of such tests themselves, but to determine the value for service under repeated stress of some strong heat-treated alloy steels.

The tests are made in reversed bending on Upton-Lewis machines but instead of the flat bar necked with a radius of 0.5 in., which Mr. Moore uses for the Upton-Lewis, a round bar, reduced from 0.35 in. to a diameter of 0.23 in. with a 1-in. radius, polished to a mirror finish with complete elimination of circumferential scratches. Spring deflection is measured with an Ames dial. The machines run at 400 to 525 alternations per minute. No difference is found due to different speeds in that range. For a given Brinell hardness, these bars show endurance limits practically the same as Mr. Moore's Farmer tests and above his Upton-Lewis figures.

The existence of an endurance limit is so clearly indicated by Mr. Moore's tests and corroborated by our own tests, and is so clearly the important figure to determine that we seldom work at stresses lower than will give a life of 100,000 alternations. Both Mr. Moore's work and our own indicate that the endurance limit in the Upton-Lewis lies within a small range of stress at the upper end of which the bar will break in about one-half million alternations and at the lower end of which the bar will stand one and one-half million alternations without breaking or any sign of damage, such as a decrease in stiffness.

When a bar has gone one and one-fourth to one and one-half million alternations unbroken, instead of continuing to hundreds of millions at that stress, the stress is raised about two and one-half per cent and the bar run another one and one-fourth to one and one-half million without removing from the jaws, so as to continue to stress the same point. If at the increased stress the bar stands another one and one-fourth to one and one-half million, the stress is again raised.

In the great majority of cases, a bar which has been run at a stress slightly below the endurance limit, when run at a second higher

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[1] C. E. Strohmeyer, *Proceedings*, Roy. Soc. Lond., Vol. 90, p. 411, 1914.

[2] J. C. Smith, *Journal*, Iron and Steel Inst., No. 11, 1910.

[3] H. J. Gough, *The Engineer*, Vol. 132, p. 159, 1921.

Mr. Gillett.

stress it shows a longer life than a previously unstressed similar bar initially stressed at the second stress.

The beneficial effect of under-stressing is quite evident. If the bar has been improved so that it will do better at a stress higher than that at which it was originally run, it seems obvious that it must also have been improved for operation at the lower stress. Hence we feel justified in raising the stress rather than continuing to run for many millions of alternations.

Our experience agrees exactly with Mr. Moore's in finding that there is no direct relation between endurance limit and proportional limit, Izod figure or Stanton figure, but that there is a fairly close relation between endurance limit and tensile strength or Brinell number. Probably the real relation is between tensile strength and endurance limit, but since Brinells can and should be made on every endurance bar itself while tensile tests cannot, we practically use the Brinell figures instead of the tensile strength figures.

On a given class of alloy steels which are closely related, the endurance limit varies with the Brinell hardness. We have some evidence that, at least in the harder steels, the alloy steels as a class have a higher endurance limit for a given Brinell hardness than a plain carbon steel, but we do not consider this fully proved. It may be that the higher draw temperature required by the alloy steels gives better release of internal strains.

We have applied the rise-of-temperature test to the Upton-Lewis machine and find that at a Brinell hardness of 250 the stress at which the rise of temperature is first detectable agrees exactly (65,000 lb. per sq. in.) with the endurance limit determined by the Upton-Lewis machine, using the same shape and size of test bar in both cases. At 400 Brinell hardness, the rise-of-temperature tests run about 115,000 lb. per sq. in. while the endurance limit is about 100,000 to 105,000 lb. per sq. in. At 460 Brinell hardness, the rise-of-temperature figure is about 130,000 lb. per sq. in., but the endurance limit is only about 105,000 lb. per sq. in. The indications so far are that the alloy steels drawn to a hardness above 400 are not appreciably improved in endurance limit, though the stress for first rise of temperature is raised.

It is not clear whether the lack of improvement in the harder steels is due to insufficient release of internal strains or whether the martensitic needle structure which is retained by the steel at the lower draw temperatures causes a non-uniform distribution of stress, so that the calculated stresses are lower than the true local stress.

Mr. Gillett. We are inclined to believe from the evidence so far at hand that internal notches, such as inclusions, are of equal importance with surface finish.

Both Mr. Moore and Mr. McAdam have kindly sent us bars failing at widely varying lives at the same stress or showing longer life at a higher stress than a similar bar. Examination of these is not yet complete but we note one difference between the Illinois and the Annapolis bars that may perhaps be one factor in the failure of the Annapolis bars to show a well-defined endurance limit. The Illinois bars have some very fine circumferential scratches and the fracture has a strong tendency to follow these, jumping from one of the deeper scratches to another. The Annapolis bars were finished circumferentially and the scratches are much deeper than on the Illinois bars. There must be greater local concentration of stress at the base of the scratches on the Annapolis bars. Such bars might fail in long time runs when a bar free from deep circumferential scratches would not.

Mr. Schwartz. MR. H. A. SCHWARTZ (*presented in written form*).—Since the authors have confined their systematic investigations to rolled materials, the results obtained by Mr. W. W. Flagle at the Research Department of the National Malleable Castings Co. may have some additional interest as being confined to cast materials. These experiments have been completed so far as they apply to malleable cast iron.

Our experiments were on Farmer rotating beam tests. Our specimens, however, had a radius of 5 in. instead of about 10 in. at the center or active portion of the specimen. The results are plotted in Fig. 11, and for comparison, Moore and Kommers' results on Armco Iron.[1] The writer believes that the endurance limit here shown agrees with a few tests by Mr. Moore (verbal communication) who obtained 26,000 lb. per sq. in. by actual test and 25,000 lb. per sq. in. by the rise-of-temperature method.

It would appear that the presence of "secondary" graphite is without effect on the endurance limit and increases the life at higher loads. It has sometimes seemed as though the graphite acted to stop inter-granular cracks from penetrating further. Failure by grain separation has always characterized malleable iron.

Fatigue tests on cast steel have been much hampered by the difficulty of securing mechanically sound specimens. We as yet know nothing, in this laboratory, as to fatigue limits in cast steel. The path of rupture in such steels is, however, very different from that through malleable cast iron. In pearlitic hypo-eutectoid steels the path of rupture travels, at random, through the ferrite but does not appear to be inter-granular. It is most gratifying that the investi-

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[1] *Bulletin No. 124*, Engineering Experiment Station, University of Illinois.

Mr. Schwartz.

gation is to be continued, by the ingeneous machines developed under Mr. Moore's supervision, into the realms of pure reversal of loads.

The rotating-beam test has the advantage of cheapness, simplicity and speed. The distribution of stresses is, however, very complex. The stress in any given outside fiber varies harmonically through a period corresponding to the rate of rotation and with an amplitude double the calculated maximum fiber stress. It follows that the strain in a given outside fiber is never the same as that of the two fibers adjacent to it in the surface. Nor is the strain the same as that of the next fiber toward the center except at the two moments in each cycle when the fiber is on the neutral axis. Thus there is constantly a longitudinal shear set up between adjacent fibers as well as the reversal of load calculated from the beam formula. Further, in the ductile metals at least, the fatigue limit is above the elastic limit, hence all tests are made under conditions in which the calculated stress is without definite meaning since the distribution of stress and strain is no longer elastic.

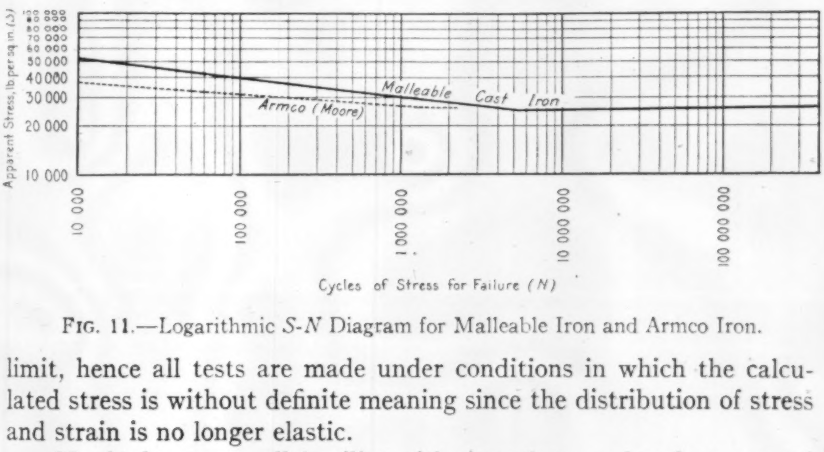

FIG. 11.—Logarithmic S-N Diagram for Malleable Iron and Armco Iron.

No doubt we are all familiar with these facts and make a mental allowance when applying our knowledge. Nevertheless a word of caution to the effect that the calculated stress does not actually exist anywhere in the specimen and that uncalculated shearing stresses do exist may not be out of place.

In conclusion it may be well to record that, in this laboratory, we were originally of the opinion that the relation of stress to life would be an exponential function throughout. All of our experiments however have tended to convert us to the belief that a true endurance limit exists, or at least a sufficient flattening out of the curve to be equivalent to such a limit from an engineering view point.

Mr. Kimball.

MR. A. L. KIMBALL.—Mr. Moore has already emphasized a danger in the use of internal angles and notches in stressed engineering

Mr. Kimball. members because failure due to fatigue action readily starts at points of high local stress. Experiment shows that the danger of failure under static loading, when high local stress exists, is not so great because a redistribution of stress results when the elastic limit is exceeded at the highly stressed points.

Since the evidence thus far seems to show that the danger of fatigue failure depends on the magnitude of local stresses, it would seem that a method by which we may determine the magnitude of local stresses should be of value in the study of fatigue. This is what is accomplished by the Coker photo-elastic method by which the stress distribution in an engineering part is determined by making a transparent model of that member, applying the loading and studying the optical effects produced by that loading. The underlying principle of this method is the well-known law by which transparent materials become double refracting in proportion to the magnitude to which they are stressed. An optical arrangement is used by which a beam of light from a projecting lantern is polarized by means of a polarizing prism, passed through a quarter wave plate which alters the plane polarized light to circularly polarized light. It is this circularly polarized light which is passed through the member which is under stress and is altered in such a way that when the light transmitted through the specimen is analyzed by means of another polarizing outfit and projected on to a screen the resulting image shows a color distribution which can be used as a quantitative measure of the stress distribution in the specimen. In order to determine the stress corresponding to a given color, a piece of the same material of which the model is made has a known stress applied to it and the resulting color directly observed. In that way a table of stress magnitude and color can be made and used to interpret the colored image of the stressed specimen. For a complete determination of the stress at every point, extensometer measurements of the change in thickness of the model are necessary as well as the polarized light analysis. The polarized light analysis gives the stress completely at boundaries and internal angles, but in order to completely determine the stress at points remote from boundaries the extensometer measurements also are necessary. Since in nearly all cases the maximum stress is at a boundary, the polarized light analysis is usually sufficient.

The material which Mr. Coker found to be most useful for this work was a transparent sheet celluloid from $\frac{3}{16}$ to $\frac{1}{4}$ in. thick, because comparatively moderate stress produced a considerable color change, making it good for optical examination and because a given stress produced comparatively large strains making it good for accurate extensometer measurements of the change in thickness. The chief **Mr. Kimball.** difficulty with this material is that most of that produced commercially is subject to initial stress, and the sheets must be carefully examined before purchasing for this use.

A question that often arises in the mind of one not familiar with this method is how we know that the stress in a model of an engineering part made of a totally different material will be distributed in the same way as in the original part. The answer to this question is that according to the laws of elasticity all materials which are sufficiently fine grained in structure to be substantially homogeneous, when loaded in the same way will have exactly the same relative stress distribution whether the elastic modulus be large or small, provided the material is not so badly strained that its shape is altered as will take place in the case of a rubber model. This law was checked experimentally by Mr. Coker for the case of a circular hole in a plate in which he found by careful extensometer measurements that the stress in a steel plate and in a celluloid plate containing holes of exactly the same size corresponded.

Plates of celluloid with notches and elliptical holes of various eccentricity have been studied by this method and the stress at the boundaries determined by direct measurement to an accuracy of about 3 per cent, when the color image is good. When the shape of an engineering part is at all complicated, the usual engineering method of determining the stress is likely to give results as much as 200 per cent in error, whereas by the construction of a model of celluloid and making a color observation the approximate value of the maximum stress can be directly observed. The only limitation which makes it impossible to make a suitable model in some cases is that the stress system has to be always represented in a single plane, because this method solves only cases of plane stress or cases where the directions of the stresses all lie in a single plane normal to the direction of the transmission of the polarized light.

In closing, let me say again that an interesting line of study in connection with this work on the fatigue strength of materials will be to compare the fatigue strength of specimens with notches and internal angles with the maximum local stresses in those notches and internal angles, with the idea of determining quantitatively how close a relation there is between the fatigue strength and the maximum local stress in the specimen.

The photo-elastic method offers a possible means of making a reasonably close measure of this maximum local stress.

Mr. Marston. MR. ANSON MARSTON.—I was very much interested in the presentation by Mr. Kimball of the method of measuring stresses by polarized light. I want to read into the record a little history on this subject. Work with polarized light in studying stresses began at a very early date. The method first came to my attention in the winter of 1892–1893, when I happened to be doing some graduate work at Cornell University. Mr. C. L. Crandall, on the initiative of the director, Mr. E. A. Fuertes, suggested to me that we could use polarized light in the determination of the stresses in friction bridge rollers. In looking up the history of the subject at that time, I found that Mr. Louis Nickerson had published a paper in the *Transactions* of the Am. Soc. Civ. Eng., Vol. III (1875) on "A Record of Experiments Showing the Character and Position of Neutral Axes, as Seen by Polarized Light." I also found that Mr. Carus Wilson, a well-known physicist, had published an article in the *Philosophical Magazine,* December, 1891, entitled "The Influence of Surface Loading on the Flexure of Beams," in which he gave the lines of stress as found experimentally by polarized light.[1]

I went ahead at Cornell and at the Iowa State College, to apply this method to the measurement of stresses in bridge rollers. My work was published in the *Physical Review*, September-October, 1893, and in the *Transactions* of the Am. Soc. Civ. Eng., August, 1894. In the latter paper the lines of stress in bridge rollers were shown as found by the dark bands observed with crossed Nicols prisms, and two colored plates were published showing the color bands observed with parallel Nicols prisms. A table of differences of principal stresses corresponding to the different colors also was given, and it was shown that the colors checked with a rigid mathematical analysis of the stresses.

The color effects are not direct measurements of the intensities of the stress except where the stress is purely in one direction, a very unusual occurrence in stress problems requiring study by this method. In the case of beams, as we all know, at each point there are two principal stresses, at right angles to each other, and in such cases the color effects are simply measurements of the numerical differences (at different points) between these principal stresses, and do not enable the direct determination of the numerical stress values. I understand, however, that in the recent work (which Mr. Kimball has described) a method has been developed of measuring the sums

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[1] The writer has learned today that Maxwell discussed stress study applications of polarized light in the *Transactions* of the Royal Society of Edinburgh, in 1853. The writer does not know how much earlier the principles involved were discovered by physicists.

Mr. Marston. of the principal stresses, by calipering the actual deformations at different points of the material, at right angles to the plane of stress, which deformation is proportional to the sums of the principal stresses at the corresponding points. Since the color effects give corresponding measurements of their differences, the two principal stresses then can be computed readily.

My own work was hand work, without the aid of color photography and the other refinements recently developed. I am very much interested in the recent development of this method, and think it will have a wide application.

Mr. Templin. MR. R. L. TEMPLIN.—Mr. Moore has already indicated to you that there has been some work done on non-ferrous metals and is still being done relative to the determination of the fatigue limits, if there is such a thing in non-ferrous metals. You will note that in the paper presented care was used to stipulate ferrous metals. The evidence in regard to the non-ferrous metals is not entirely conclusive as yet, but the indications are that we do not have such a definite fatigue limit as occurs in the ferrous metals. It is quite true there is a sort of an arrest in the curve after a certain number of repetitions of stress, but there is also evidence that after this arrest has occurred in the curve, that later the curve starts downward again, approximately parallel to the first part of the curve. I understood from Mr. Moore that they have been looking for this in ferrous metals, but have not as yet found it.

In an article published in *The Engineer* of August 12, 1921, by Mr. H. J. Gough some methods of fatigue testing are described. One of the methods he used involved the change in rate of deflection of the specimens under fatigue action. Most men in a commercial laboratory always welcome a short time test if it can be shown that this short time test is a reliable index of the property they are studying, so we found occasion to try out the method suggested by Mr. Gough in which he measured the change in rate of deflection for some of the non-ferrous alloys. We were particularly interested in the alloy that is made by the Aluminum Co. of America called 17S, and incidentally we tested a specimen of a magnesium alloy.

In all of the tests which were made, using the method as suggested by Mr. Gough, we could find no change in rate of deflection that would compare to the fatigue limit, or limiting fiber stress. Nearly all of the specimens were stressed to a point above the static yield point of the metal without any change from a straight line deflection curve. Specimens were run at a number of different speeds throughout the range of 100 revolutions per minute to 1400 revolutions per minute.

Mr. Templin. The form of test specimen used was the cantilever type, as suggested by Mr. McAdam, and the deflection measuring device was somewhat similar to the device as described before this Society by Mr. Francke two years ago.[1] Dead weight was applied to the specimen and deformation readings taken and plotted against the computed stress. Straight line curves were obtained in every case except that of the magnesium alloy, which did, however, give a straight line curve above the yield point as determined from the static stress.

I might say for the long time tests that we use a testing machine that is very similar to the one used in the joint investigation, that is, of the rotating beam type, except that we use a specimen considerably larger than the one used in the joint investigation. The specimen is 30 in. long and 10 in. between load points, and 1 in. in diameter. Specimens are tested at a speed of 1400 r.p.m. Our tests so far extended out to slightly over 300,000,000 repetitions of stress.

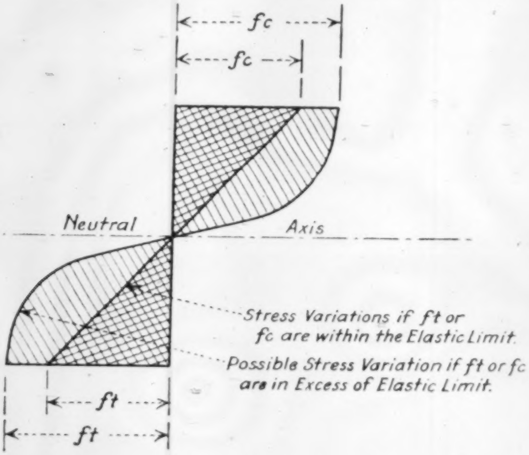
fc
fc
Neutral
Axis
Stress Variations if ft or fc are within the Elastic Limit.
Possible Stress Variation if ft or fc are in Excess of Elastic Limit.
ft
ft

FIG. 12.—Diagram Showing Stress Variation over Cross-Section of Specimen.

Mr. Lessells. MR. J. M. LESSELLS (*presented in written form*).—In *Bulletin No. 124*, Prof. Moore's results show that in some cases the endurance limit, or fatigue limit, is higher than the proportional elastic limit. To all those interested in fatigue phenomena, these results are very interesting and seem vitally important if a true interpretation of these investigations is to be obtained. The fact that endurance limit for certain classes of steels appears to be higher than the proportional elastic limit coincides with the work of other investigators.

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[1] W. J. Francke, "An Apparatus for Delicate Flexure Tests and Some Results of Such Tests," *proceedings*, Am. Soc. Test. Mats., Vol. XX, Part II, p. 372 (1920).

Mr. Lessells. The hypothesis put forward by myself is that since it is possible by a process of loading and unloading a specimen in a tension testing machine to raise the elastic limit artificially, the same possibility appears to be present in fatigue testing, and where the ratio of proportional elastic limit to ultimate strength is less than some value approximately equal to 0.5 this peculiarity may occur.

It would seem that where this ratio is lower than 0.5 there is more liability to raise the elastic limit by strain, and if this hypothesis is correct, then the endurance values which are in excess of the proportional elastic limit require to be corrected.

The following table has been compiled from the values given in Table 3 of *Bulletin No. 124:*

No.	MATERIAL.			STATE.	PROPORTIONAL ELASTIC LIMIT TO ULTIMATE STRENGTH.	ENDURANCE LIMIT TO PROPORTIONAL ELASTIC LIMIT.
9	0.02 per	cent	carbon	As received	0.38	1.6
51	0.02	"	"	Hot Rolled	0.62	0.735
51	0.02	"	"	Reduced	0.95	0.58
50	0.02	"	"	Cold Drawn	0.64	0.74
50	0.02	"	"	Annealed	0.47	1.1
50	0.02	"	"	Annealed	0.49	0.9
4	0.37	"	"	Normalized	0.48	0.95
4	0.37	"	"	Sorbitic	0.79	0.71
4	0.37	"	"	Sorbitic	0.66	0.73
10	0.49	"	"	Sorbitic	0.70	0.71
3	0.52	"	"	Normalized	0.46	0.92
3	0.52	"	"	Sorbitic	0.72	0.68
6	0.93	"	"	Pearlitic	0.33	1.1
6	0.93	"	"	Sorbitic	0.52	0.93
6	0.93	"	"	Troostitic	0.51	1.0
1	1.20	"	"	Normalized	0.50	0.85
1	1.20	"	"	Sorbitic	0.67	0.77

From an examination of these results the previous contention will be evident.

In cases of fatigue work where the applied stresses are in excess of the elastic limit and are produced by bending, the ordinary beam formula will not apply, since stress will not be proportional to strain and a further correction especially for combined stress investigation would appear to be necessary. In Fig. 12 is shown how these stresses would vary over a cross-section.

As an aid to the interpretation of the results obtained to date from fatigue testing, it would seem to be profitable to have Mr. Moore comment on these points.

Mr. Lessells. It must be clearly understood that such questions are not put with an antagonistic feeling but with a view to seeking the truth regarding fatigue development.

Mr. Elliott. MR. G. K. ELLIOTT.—Almost foolish as it may seem to some to talk about fatigue tests for cast iron, still I shall avail myself of the opportunity of asking Mr. Moore if there is any reason to believe that fatigue tests of cast iron can be made and, if so, whether he thinks they will be of value. Frankly, I am one who believes that such tests would be of great value. At present, estimates of cast iron are based almost entirely upon tension and transverse tests which fundamentally are static, while very often the service conditions to which the castings will be subjected are dynamic. Many times have I seen cast irons that in transverse and tensile strength were within 10 or 20 per cent of each other but which, when exposed to dynamic forces, were as far apart as 200 per cent. It is my hope that one or more dynamic tests, including fatigue tests, can be developed and generally used because such tests probably will enable users of cast iron to detect differences that, although often very great, at present are escaping detection. Such tests also may help clear up puzzling questions about the effects of sulfides, phosphides and other inclusions and constituents of cast iron.

Mr. Dudley. MR. P. H. DUDLEY (*presented in written form*).—In *Bulletin No. 124*, the authors define the "endurance limit" as "the highest unit stress which applied in cycles of completely reversed stress can be withstood an indefinite number of times without failure." I am bold enough to state that the endurance limit of steels may be improved. I do not include specifically metals, as that would be too general, and a subject beyond my experience. I know that steel for rails, wheels and locomotives has been improved in the past forty years and the endurance limit extended in service, and what has been done in steels of the past can be improved for future service. Specifications for steels for important purposes should include the proper elements as deoxidizers. In some cases it is mass action of the metal in the design of rail heads and in other cases it is the deoxidized metal for freedom of impurities. The specific cause is traced by service tests as the steels are used. It only requires observation to distinguish the causes and trace the effects of service.

The work of Mr. H. F. Moore and Mr. J. B. Kommers has defined the endurance limit of steel on a scientific basis and those of us making steel in large quantities utilize the results of their investigations to increase the endurance limits of steel, which can be done for the present heavy axle loads of locomotives, coaches and cars.

Mr. Hall. MR. J. H. HALL.—I understand that the endurance limit is higher as the tensile strength and the yield point go up; am I right in supposing that you can improve the endurance limit of a given piece of steel by heat treating as compared to annealing; or if we want a higher endurance limit, must we get it by higher carbon?

Mr. Styri. MR. HAAKON STYRI.—About a year ago we developed at the S. K. F. Laboratory a fatigue machine for reversed axial stress, and I would like to give some results we got from temperature measurements. We found it necessary to have very large fillets to prevent breaking of the specimen where the cross-section changes. The steel tested was 1.04-per-cent-carbon steel, Brinell hardness 255, and it was tested for loads from 12,000 lb. to 55,000 lb. per sq. in. The temperature was measured after it had become constant at each increment of load going up and going down, which would require five or ten minutes for each point. It was not necessary to stop the machine to change the load. The curve we got was a very smooth curve of temperature gradually increasing with the load. At about 55,000 lb. per sq. in., we got a very rapid rise in temperature that corresponds approximately to that described in the paper for 1.20-per-cent-carbon steel, but there was no abrupt change.

Mr. Jasper. MR. T. M. JASPER (*Author's Closure*).—The following explanation is offered for the slight difference between the Illinois results for ingot iron and the Annapolis results pointed out by Mr. Tuckerman. It has been found very recently that while the Illinois ingot iron was box annealed, the ingot iron used at Annapolis was normalized. The difference in surface conditions of the specimens has already been pointed out in the discussion by Mr. Gillett.

Another point touched on by Mr. Tuckerman, and also by Mr. McAdam, was the evidence brought to bear on the existence of an endurance limit. It cannot be said definitely that the endurance limit is the absolute limit below which if we stress a material it will never fail, because of course, no one has tested a material for an infinite number of cycles of stress. There is in the laboratory at the present time, running at the endurance limit, a specimen which has gone to 750,000,000 cycles and another which has gone 550,000,000 cycles without signs of failure. We have also retested specimens that have run 100,000,000 cycles at the endurance limit by putting them in at an increased stress for another 50,000,000 cycles, and some have had the stress eventually increased 20 per cent above the original endurance limit without failure, which suggests for ferrous metals that the tendency is up rather than down after the break in the stress-cycle curve is passed.

The fact that the Annapolis tests do not show an endurance limit

Mr. Jasper. is probably due to differences in carrying out tests and in plotting results, as compared with the tests at Illinois. One factor in this difference was the fact that the machines and the specimens used were different. In the Annapolis tests, cantilever-beam specimens were used; in the Illinois tests, specimens supported at both ends of a span. Later, at Illinois, some cantilever specimens were tested, and they gave slightly different results from the supported-beam specimens of the same material. The type of machine and the specimen used have some influence on the test results.

We would agree that Mr. McAdam's term "practical endurance limit" accurately describes the limits found and reported by the Investigation of the Fatigue of Metals.

In answering Mr. Lessells' questions I would say that as shown by the paper the correlation between the elastic limit and the endurance limit is not very marked; it is not comparable to the correlation between the endurance limit and tensile strength. The tensile strength is obtained in a test to failure. A fatigue test is a test to failure. Even the Brinell test is a test to a certain type of failure; therefore, the point may be answered in this way, that it is not thought that there is a close correlation between the elastic limit and fatigue strength.

Mr. Lessells notes that in the calculation of stresses due to load on a beam or cantilever, we are dependent on the stress being proportional to strain and asks what correction is applied when the computed stresses are in excess of the elastic limit, and, therefore, applicable to the case where the endurance limit is in excess of the elastic limit. The point of view adopted is that of the practical engineer. He uses the formula $S = Mc/I$. This, however, holds, strictly speaking, only within the elastic limit of the material. This formula is applied in the particular case in question to the material after it has gone apparently beyond the yield point. We do not know the real maximum stress the material reached after it had gone beyond the yield point because beyond the yield point the stress-strain curve is no longer even approximately a straight line, and, therefore, theoretically speaking there should be a correction. But we have given the values of nominal stress as obtained from the formula for practical application and mentioned the method adopted by the laboratory in the publication of the results in *Bulletin No. 124*, of the Engineering Experiment Station, University of Illinois.

Mr. Elliott has asked the question as to whether fatigue tests on cast iron could be made. We have run a few specimens of malleable cast iron and would say that we would be very glad to make further tests on cast iron. Our funds are somewhat limited, however, and we could not possibly take up systematically so wide a field as we are situated today without some kind of appropriation for that purpose.

Mr. Jasper. The question has been asked by Mr. Hall, "Can we by heat treatment improve or increase the endurance limit?" The answer would be in the affirmative in general. We have to be careful in specifying what we mean by heat treatment, but, in general, I would say that you can improve most steels if you use the right heat treatment.

The suggestion has been made that the static properties of a ferrous metal are not changed during fatigue testing so that there is obtained no indication of the approach of failure when the stress is above the endurance limit. We have no evidence to offer on this point but wish to indicate certain effects of repeated stress on the static properties when the stress in fatigue is below the endurance limit. A few static tests have been made on Farmer specimens which have run 100,000,000 cycles without failure at or slightly below the endurance limit. The results have been compared with Farmer specimens which have not been put in a fatigue testing machine. We find that the static properties, such as yield point and ultimate strength, are slightly improved in every case for the specimens that had previously run 100,000,000 cycles without failure. The improvement is from 5 to 8 per cent on the specimens which were used. This suggests to us that the outside skin of the specimen which received the maximum stress in fatigue is probably improved more than this.

We have not, as yet, been making tests in which a large factor of rest enters. After 6 to 8 months' rest we have run specimens which had previously run to 100,000,000 reversals at a stress higher than the original stress. The results of the experiments do not show whether the apparent increase in strength is entirely due to cold working in the original run or whether it has been effected by rest. Some time ago a series of short time tests was made by Mr. W. S. Putman of the University of Illinois in which some specimens were given two or three rest periods of 24 hours. These specimens gave no higher results than did specimens run continuously to failure.

It might be thought that the *S-N* diagram shown in Fig. 12 of the paper could be used in design, and that a stress above the endurance limit might be used as the basis of design provided the number of cycles of stress during the life of the structure or machine did not reach the value shown on that diagram. A study of *S-N* diagrams for wrought ferrous metals shows that the "break" in the diagram rarely occurs beyond 1,000,000 cycles of stress, and, in general, if the stress is increased by as little as 10 per cent above the endurance limit the "life" would probably be no longer than 500,000 cycles of stress. This would mean a "life" of only 100 days at a rate of repetition of stress of 3 cycles per minute. It is not thought safe to use any stress above the endurance limit as a basis of design for any part subjected to reversed stress.

SOME MEASUREMENTS OF THE SHAPE OF BRINELL BALL INDENTATION.

By Fred E. Foss[1] and R. C. Brumfield.[2]

The greater portion of the data which forms the basis for this paper was obtained by the authors in a study of Problem S. B. 7 of the Hardness Testing Committee under the Engineering Division of the National Research Council, "A Comparison of Depth with Diameter-Measuring Apparatus to Determine the Conditions under Which Each Should Be Used." This paper contains a description of the methods used in the investigation, an analysis of the results obtained and the conclusions arrived at, together with a discussion of certain allied data which have no direct bearing on this particular problem.

In the discussion of these tests the Brinell hardness number has been assumed to be the load in kilograms divided by the true area of the surface of the indentation produced by a 10-mm. steel ball.

In making the tests, the following objects were aimed at:

1. To make an accurate measurement of the actual indentation made by the Brinell ball in each test, and from this to obtain the actual hardness number.
2. To compare the hardness numbers as computed on various assumptions, from the depth-gage readings and from measurements of the actual depth and diameter of the impression, with this actual hardness number in order to determine which method gave the most nearly correct results, and to discover the cause of any discrepancy.
3. To compare the consistency of the results obtained from each method.
4. To study the effect on hardness numbers of variation of the load and time during which the full load was maintained.

In order to make the tests as comprehensive as possible, it was thought desirable to run them on as large a variety of metals as could be obtained. Accordingly, through the cooperation of Mr. C. L. Warwick, Secretary of the American Society for Testing Materials, we were able to get from the Midvale Steel Co. six samples of alloy steel, and from the American Brass Co. eight samples of hard and soft brasses and bronzes. The tests also included carbon steels of different carbon content and cast iron from our own laboratory. All the steel samples were tested under at least two different heat treatments. The range of hardness numbers for the tests was from 50 to somewhat over 700. The analyses of the metals are given in Table I.

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Three different types of depth gages, the Olsen, Amsler and one other, were investigated. Schematic drawings of the Olsen and Amsler gages are shown in Figs. 1 and 2. The Olsen gage, shown in Fig. 1, has two contact points, *A-A*, with the test piece. These are placed symmetrically with the center line of the ball and transmit the motion through the pivot *B*, and the equalizing bar *C* to the plunger of the dial *D*, on which it is possible to estimate readings to 0.001 mm. This gage is a true averaging gage, as long as the test piece remains a true plane, and has the advantage of simplicity of construction and positive transmission of movement. The gage is clamped to the shank, which carries the ball, about $1\frac{1}{2}$ in. above the center of the ball.

TABLE I.—COMPOSITIONS OF THE METALS USED IN THE HARDNESS TESTS.

BRASSES AND BRONZES.
All values in per cent.

Designation.	Copper.	Zinc.	Lead.	Tin.	Iron.	Phosphorus.	Manganese.
Hard Brass No. 1 Soft Brass No. 2	62.47	34.88	2.62	0.0	0.03	....	....
Hard Tobin Bronze No. 3 Soft Tobin Bronze No. 4	60.16	39.09	0.04	0.69	0.02	....	....
Hard Phosphor-Bronze No. 5 Soft Phosphor-Bronze No. 6	94.89	0.42	....	4.32	....	0.35	....
Hard Manganese Bronze No. 7 Soft Manganese Bronze No. 8	59.74	38.27	....	0.74	0.90	....	0.35

ALLOY STEELS.
All values in per cent.

Designation.	C	Mn	P	S	Si	Ni	Cr	V
B—1322	0.24	0.85	.....	.....	0.21	29.30	....	....
No. 4—10851	0.11	0.34	0.010	0.031	0.13	3.00	0.58	....
No. 6—9946	0.34	0.59	0.027	0.037	0.20	1.22	0.43	....
No. 4—10966	0.30	0.71	0.010	0.031	0.22	2.84 2.84	0.70 0.71	....
MKD—455	0.45	0.57	0.012	0.019	0.21	.....	1.51	0.28
No. 12—4358	0.50	0.68	0.021	0.030	0.23	3.45	....	....

CARBON STEELS.
(Per cent of carbon approximate only.)

0.5—C—T	0.5-per-cent carbon, tempered.
0.5—C—W	0.5 " " water quenched.
0.5—C—O	0.5 " " oil quenched.
0.5—C—A	0.5 " " cooled in air.
0.5—C—N	0.5 " " normal, as it came from the mill.
Samples of	0.9 " " steel are indicated by similar notation.

GRAY CAST IRON.
Ordinary commercial gray cast iron, exact composition not known.

The Amsler gage, shown in Fig. 2, transmits the motion of the ball through the sliding sleeve *A*, the small friction roller *B* and toothed gear *G*, to the indicating needle *D*. Readings can be estimated on this gage also to 0.001 mm. As this gage has no device for averaging, the tendency is to give readings too large or too small if the angle of inclination of the surface of the specimen with the horizontal changes during the application of the load. The friction roller is liable to slip if the instrument is jarred during a test and if the transmission sleeve is raised and released it is found that the reading of the dial changes.

Both gages described gave accurate readings when compared with an Ames dial.

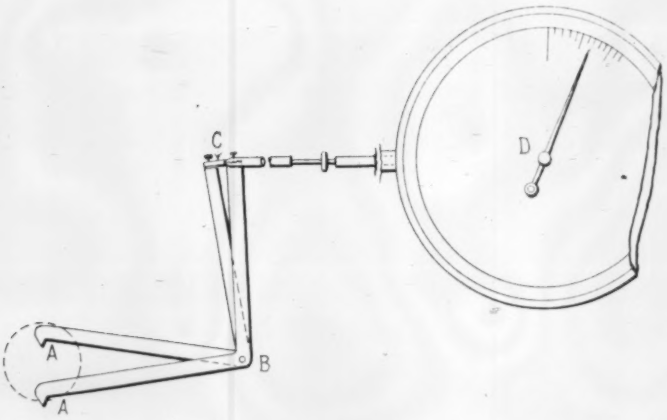

FIG. 1.—Olsen Depth Gage.

The other gage referred to was used in some tests, but was discarded as the results were very inconsistent. The authors believe it is faulty in construction. The paper, consequently, deals only with the results obtained from the two gages described.

The microscope for measuring the diameter of the impression was of the ordinary non-traversing type which magnifies to about 10 diameters and permits the diameter of the impression to be estimated to the nearest 0.01 mm.

The balls which were used were furnished by the Hoover Steel Ball Co., of Ann Arbor, Mich., and were of the ordinary grade, used for Brinell hardness work. They were supported in a metal ring and turned under the plunger of a 0.0001-in. Ames dial and found to be quite uniform, none of them varying more than 0.0001 in. The balls marked "special" in the table were furnished by Mr. Hultgren of the S. K. F. Research Laboratory, Philadelphia, and were especially manufactured with a view to testing very hard steels. They were, consequently, as hard as obtainable.

The loads were applied by an ordinary 50,000-lb. Olsen testing machine, which had been calibrated with levers up to 20,000 lb. and found to be accurate. The machine was sensitive under low loads to about 10 lb. The top bar was removed from the scale beam in order that temporary overloads might not be applied. The load was applied rather slowly by a hand-wheel in order to avoid temporary overload due to the inertia of the moving parts. A hydraulic machine was available for applying the loads but since it was not equipped for attaching the depth gages and there was some uncertainty as to the true value of the load, due largely to the viscosity of the oil and friction, it was not used. An initial load of 40 lb. was chosen because it was necessary to have some starting point and this was as low a load as could be readily and accurately put on the machine. On most of the impressions an electric contact reading was also taken, hence the exact effect on the impression by the initial load is known.

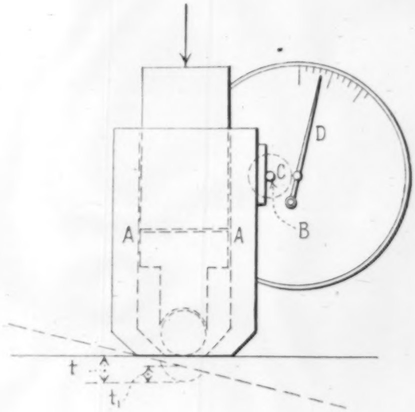

Fig. 2.—Amsler Depth Gage.

In order to arrive at the true shape of the impression left in the metals by the Brinell ball, the instrument illustrated in Fig. 3 was built in the laboratory of Cooper Union. This instrument consists of a metal block *A* which rests and is free to slide on the base *B*, being moved by the adjusting screws *C*. The amount of the movement is recorded by the three Ames dials S_1, S_2, and *E*, each of which reads to 0.001 in. The specimen is clamped in block *A*, and placed directly under the needle *N*, which is fastened in the vertical plunger *D*.

The movement of *D* is recorded by the Ames dial, *F*, which reads to 0.0001 in. and has been calibrated by the U. S. Bureau of Standards. The plunger *D* is moved by the adjusting screw *G*, the back lash in which is taken up by the coil spring *H*. Screws, *I*, bear against plunger *D* through fabricoid blocks, thus eliminating any movement sidewise. The whole system from *N* to *F* is swung on the vertical post *K* and is adjustable in rotation and transversely. The diagonal strut *L* is simply a brace to steady the plunger system and eliminate vibrations. It is capable of adjustment so that it always lies approximately in the plane of *N*, *K* and *F*. The whole plunger system is insulated from the base of the instrument, and a micro-telephone receiver with a battery is connected at the points *M*. Through this receiver, contact between the needle *N* and the specimen is detected.

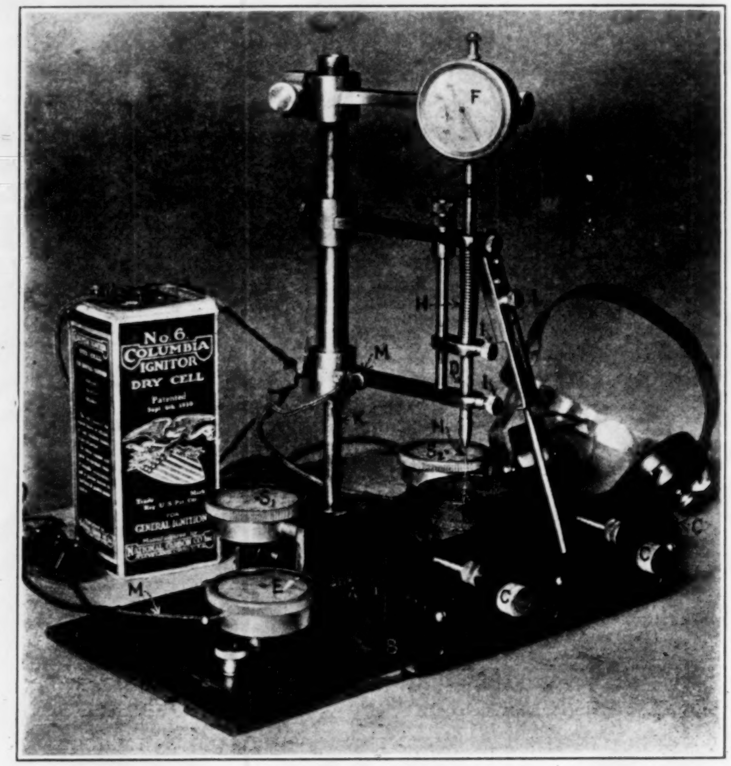

FIG. 3.—Instrument Used in Cross-Sectioning Brinell Ball Impressions.

Four sets of tests were run in the Electrical Laboratory of Cooper Union to determine the accuracy of this instrument. Readings were taken at first contact with a steel plate, the instrument being connected to a galvanometer. An average of about six readings was taken for each set. As a source of electro-motive force a single dry cell with one megohm and one-half megohm respectively as series resistances was used. The average for the four sets of readings for these two currents gave a difference in the spark gaps for the two of 0.000033 in., with the maximum variation from the mean of 0.0000035 in. In our hardness measurements no results were recorded closer than 0.0001 in.

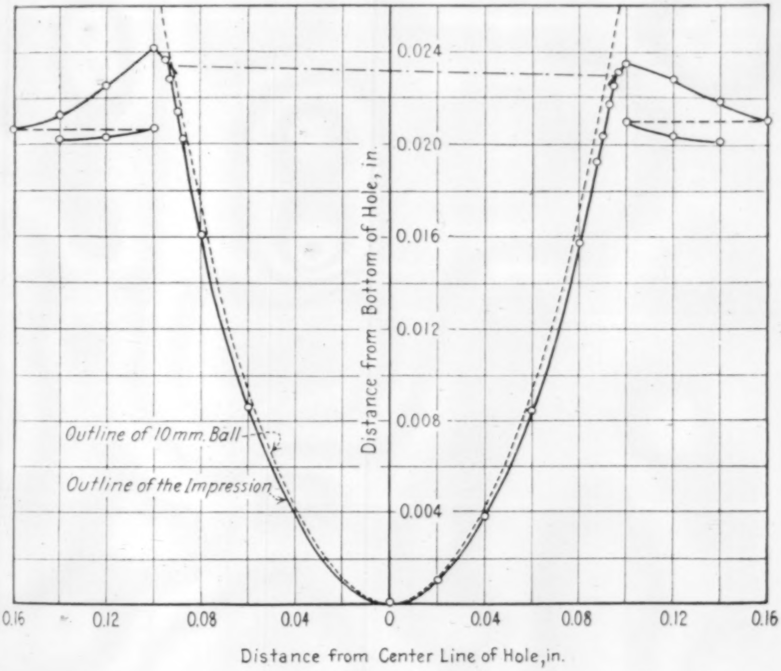

FIG. 4.—Diagram of Section of Brinell Ball Indentation Obtained with Instrument, Fig. 3. Hard Phosphor-Bronze, 3000-kg. Load Held for 30 Seconds.

The routine procedure for measuring the diameter for any impression was as follows: The specimen was placed in the instrument with the center of the hole approximately under the needle point, and the contact reading at this point obtained on dial *F*. The needle was raised about 20 or 30 dial divisions; block *A* was moved longitudinally, taking contact readings on dial *E* at each side of the center of the impression. The dial E was set at the mean of these two readings for the longitudinal center of the indentation. The process was then repeated transversely, using dials S_1 and S_2. A second trial was sometimes necessary to obtain the exact reading of E corresponding to a position of the needle in the center of the impression.

In all cases the chords measured in the two directions at right angles were found to be practically equal, showing that the body of the impression was symmetrical and not egg-shaped as has sometimes been stated. Some measurements were also made at an angle of 45 deg., with the same results. After the center of the hole had been located, a complete cross-section of the indentation was made, readings being taken at intervals of about 0.02 in., except at the edges of the hole, where the interval was often reduced to 0.001 in.

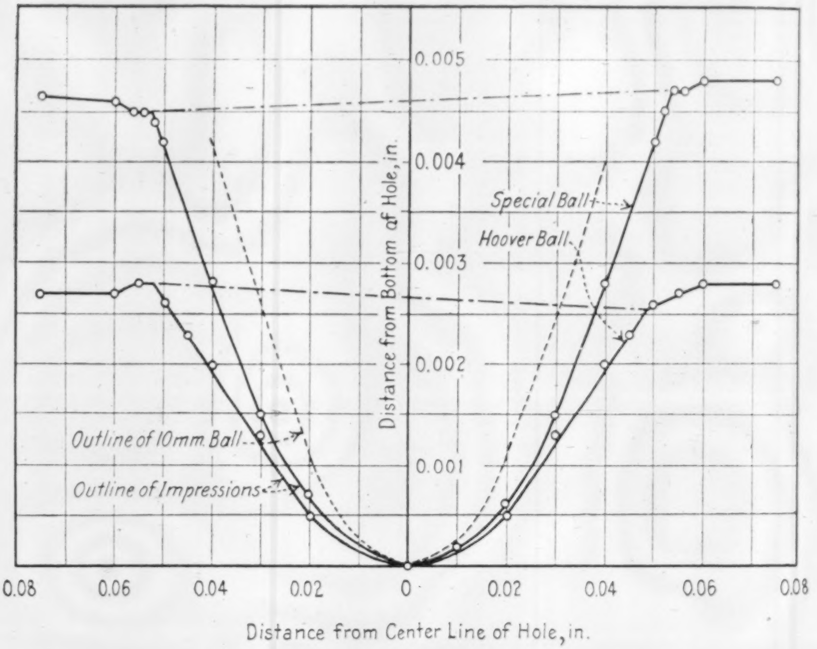

FIG. 5.—Diagram of Section of Brinell Ball Indentation Obtained with Instrument. Fig. 3. Alloy Steel No. 12–4358, Water Quenched from 1000° C., 3000-kg. Load in Hoover Ball Test, Held for 30 Seconds, Load in Special Ball Test, Held for 20 Seconds.

Readings were extended beyond the edge of the hole in many cases until all measureable effect of the upsetting of the metal had disappeared. These readings were plotted on cross-section paper and the actual diameter and depth of the impression read from the paper

TABLE II.—TABULATION OF MEASUREMENTS AND COMPUTATIONS FOR ALL CROSS-SECTIONS.

Designation.	Ball Used.	Load, kg.	Held at Full Load, seconds.	Diameter of Impression, mm., by		Depth of Impression, mm.							Computed Diameter of Sphere which Fits the Impression.	Hardness Number as Computed from:		
				Instrument, Fig. 3.	Microscope.	Instrument, Fig. 3.	Olsen Gage.[1]			Amsler Gage.[1]				True Area.	Assumed 10-mm. Impression.	
							40-lb. Initial.	Full Load.	40-lb. Final.	40-lb. Initial.	Full Load.	40-lb. Final.			Diameter, Col. 5.	Depth, Col. 7.
1	2	3	4	5.	6	7	8	9	10	11	12	13	14	15	16	17
BRASS AND BRONZE.																
Hard Brass, No. 1	Hoover	3000	30	5.49	5.56	0.790	0.012	0.878	0.714	.....	.....	.....	10.40	116	116	121
				5.54	5.53	0.800	0.015	0.844	0.674	.....	.....	.....	10.40	115	114	120
				5.54	5.58	0.803	0.009	0.877	0.713	.....	.....	.....	10.35	115	114	119
				5.48	5.53	0.793	0.010	0.874	0.699	.....	.....	.....	10.27	117	117	120
Soft Brass, No. 2	Hoover	500	30	3.28	3.30	0.262	0.019	0.280	0.237	.....	.....	.....	10.54	58	58	61
				3.30	3.31	0.272	0.021	0.280	0.239	.....	.....	.....	10.32	57	57	59
				3.30	3.30	0.269	0.021	0.293	0.243	.....	.....	.....	10.42	57	57	59
Hard Tobin Bronze, No. 3	Hoover	3000	30	4.90	4.98	0.615	0.001	0.720	0.528	.....	.....	.....	10.42	150	149	155
				4.90	4.96	0.602	0.009	0.711	0.529	.....	.....	.....	10.60	150	149	159
				4.90	4.97	0.599	0.008	0.711	0.531	.....	.....	.....	10.60	150	149	159
Soft Tobin Bronze, No. 4	Hoover	500	30	2.85	2.80	0.183	0.011	0.230	0.168	.....	.....	.....	11.28	78	75	87
		500		2.875	2.71	0.183	0.009	0.221	0.170	.....	.....	.....	11.48	76	76	87
		500		2.77	2.71	0.181	0.009	0.220	0.160	.....	.....	.....	10.78	81	82	88
		500		2.85	2.82	0.188	0.013	0.236	0.178	.....	.....	.....	10.99	77	77	85
		1000		3.71	3.70	0.335	0.012	0.408	0.331	.....	.....	.....	10.63	92	90	95
		1500		4.39	4.40	0.497	0.009	0.572	0.472	.....	.....	.....	10.20	94	94	96
		2000		4.93	4.91	0.623	0.012	0.732	0.599	.....	.....	.....	10.42	98	98	102
		2500		5.46	5.40	0.783	0.009	0.904	0.769	.....	.....	.....	10.38	98	98	102
		3000		5.89	5.81	0.923	0.011	1.103	0.940	.....	.....	.....	10.62	97	99	103
Hard Phosphor-Bronze, No. 5	Hoover	3000	30	4.85	5.0	0.582	.....	.....	.....	0.022	0.687	0.313	10.73	154	153	164
		3000		4.93	5.0	0.584	.....	.....	.....	0.008	0.667	0.487	10.63	149	147	164
		3000		4.93	4.96	0.592	.....	.....	.....	0.000	0.684	0.508	10.62	149	147	162
		3000		4.76	4.98	0.575	.....	.....	.....	0.003	0.675	0.496	10.46	160	158	185
		500		2.015	....	0.089	.....	.....	.....	0.015	0.136	0.079	11.49	157	156	178
		1500		3.63	3.60	0.308	0.008	0.340	0.234	.....	.....	.....	10.91	142	141	155
		2000		4.14	4.13	0.412	0.008	0.441	0.324	.....	.....	.....	10.81	143	141	155
		2500		4.57	4.61	0.521	0.007	0.524	0.404	.....	.....	.....	10.53	145	144	153
Soft Phosphor-Bronze, No. 6	Hoover	500	30	3.00	3.00	0.196	.....	.....	.....	0.063	0.228	0.176	11.65	70	70	81
		500		3.28	3.25	0.248	.....	.....	.....	0.055	0.204	0.225	11.09	58	58	64
		500		2.70	2.82	0.165	.....	.....	.....	0.011	0.192	0.154	11.22	86	86	96
		3000		6.15	6.38	1.047	.....	.....	.....	0.161	1.284	1.144	10.1	90	90	91
Hard Manganese Bronze, No. 7	Hoover	3000	30	4.88	4.90	0.593	0.008	0.681	0.500	.....	.....	.....	10.69	151	151	161
		3000		4.93	4.91	0.592	0.008	0.673	0.492	.....	.....	.....	10.79	149	147	[illegible]
		3000		4.86	4.82	0.577	0.010	0.671	0.482	.....	.....	.....	10.71	154	152	165
		3000		4.91	4.88	0.592	0.011	0.686	0.492	.....	.....	.....	10.79	149	148	161
		500		2.06	2.18	0.098	0.010	0.139	0.073	.....	.....	.....	10.92	149	149	162
		1000		2.95	2.91	0.194	.....	.....	.....	.....	.....	.....	11.39	144	146	164
		1500		3.55	3.51	0.295	0.011	0.368	0.248	.....	.....	.....	10.91	147	147	162
		2000		4.02	4.07	0.389	0.009	0.470	0.335	.....	.....	.....	10.79	151	150	164
		2500		4.52	4.56	0.483	0.011	0.585	0.438	.....	.....	.....	11.08	149	147	165
Soft Manganese Bronze, No. 8	Hoover	500	30	2.46	2.50	0.155	0.011	0.180	0.120	.....	.....	.....	10.00	103	103	103
				2.52	2.52	0.152	0.013	0.184	0.126	.....	.....	.....	10.60	98	97	104
				2.62	2.52	0.160	0.008	0.183	0.123	.....	.....	.....	10.76	92	91	99
				2.56	2.50	0.149	0.010	0.183	0.130	.....	.....	.....	11.15	96	95	107

[1] Columns 8 and 11 show readings between electric contact and 40-lb. initial load; Columns 9 and 12 show readings between 40-lb. initial load and full load. Columns 10 and 13 show readings between 40-lb initial load and final 40-lb. load after pressure is released.

TABLE II.—TABULATION OF MEASUREMENTS AND COMPUTATIONS FOR ALL CROSS-SECTIONS—*Continued.*

Designation.	Ball Used.	Load, kg.	Held at Full Load, seconds.	Diameter of Impression, mm., by		Depth of Impression, mm.							Computed Diameter of Sphere which Fits the Impression.	Hardness Numbe as Computed fro		
				Instrument. Fig. 3.	Microscope.	Instrument, Fig. 3.	Olsen Gage.[1]			Amsler Gage.[1]				True Area.	Assumed 10-mm. Impression	
							40-lb. Initial.	Full Load.	40-lb. Final.	40-lb. Initial.	Full Load.	40-lb. Final.			Diameter, Col. 5.	Depth Col. 7
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
STEEL AND IRON.																
[a]0.5 C—A	Hoover	3000	30	4.57	4.40	0.488	.....	0.61	0.41	.....	.....	.....	11.19	174	172	195
[a]0.5 C—O				3.30	3.42	0.238	.....	0.40	0.22	.....	.....	.....	11.86	344	324	400
[a]0.5 C—T				3.46	3.45	0.217	.....	.....	.....	.....	0.418	0.222	14.02	314	311	430
[a]0.5 C—N				4.26	4.21	0.392	.....	.....	.....	.....	0.545	0.487	11.97	204	201	244
[a]0.5 C—W				2.54	2.60	0.078	.....	.....	.....	.....	0.312	0.076	20.60	590	532	1260
[a]0.5 C—T				3.05	3.00	0.163	.....	0.330	0.150	.....	.....	.....	13.05	450	444	566
[a]0.9 C—T				3.07	3.10	0.147	.....	.....	.....	.....	0.346	0.146	16.28	401	387	654
[a]0.9 C—O				3.04	3.01	0.182	.....	0.370	0.188	.....	.....	.....	12.88	406	392	510
[a]0.9 C—W				2.21	2.40	0.035	.....	.....	.....	.....	0.328	0.085	34.64	790	774	2740
[a]0.9 C—A				4.07	....	0.392	.....	.....	.....	.....	0.529	0.400	10.45	233	221	244
[a]0.9 C—N				4.57	4.70	0.513	.....	0.700	0.560	.....	.....	.....	10.57	174	172	184
B—1322	Hoover	3000	30	4.94	4.98	0.610	.....	.....	.....	.....	.....	.....	10.61	147	147	156
		3000		4.93	4.90	0.620	.....	.....	.....	.....	.....	.....	10.47	147	147	154
		3000		4.93	4.92	0.621	.....	.....	.....	.....	.....	.....	10.37	148	147	154
		3000		4.81	4.81	0.600	.....	.....	.....	.....	.....	.....	10.30	154	154	159
		1000		3.08	3.02	0.230	0.006	0.365	0.203	.....	.....	.....	10.53	131	131	138
		1500		3.92	3.59	0.376	0.007	0.436	0.362	.....	.....	.....	10.58	120	119	127
		2000		4.21	4.10	0.441	0.000	0.511	0.409	.....	.....	.....	10.46	137	137	144
		2500		4.68	4.50	0.546	0.002	0.637	0.511	.....	.....	.....	10.65	137	137	146
[b]B—1322 1000° C—W	Special	3000	30	4.86	4.89	0.615	.....	.....	.....	0.027	0.781	0.612	10.22	152	152	155
		3000	20	4.90	4.91	0.627	.....	.....	.....	0.039	0.808	0.646	10.21	149	150	152
		3000	0	4.91	4.95	0.628	.....	.....	.....	.....	.....	.....	10.31	148	148	152
	Hoover	500	30	2.26	....	0.122	0.007	0.132	0.086	.....	.....	.....	10.57	124	123	131
		1000		3.02	....	0.224	0.011	0.265	0.198	.....	.....	.....	10.42	136	137	143
		1500		3.48	....	0.303	0.006	0.349	0.252	.....	.....	.....	10.32	152	153	157
		2000		4.09	....	0.420	0.013	0.491	0.396	.....	.....	.....	10.39	146	145	152
		2500		4.65	....	0.556	0.025	0.606	0.475	.....	.....	.....	10.26	140	140	143
No. 4—10851	Hoover	3000	30	5.08	5.09	0.676	.....	.....	0.599	.....	.....	.....	10.23	138	138	141
				5.00	5.08	0.650	.....	0.712	0.605	.....	.....	.....	10.25	144	143	147
				5.00	5.04	0.650	.....	.....	0.598	.....	.....	.....	10.25	144	143	147
				5.06	5.02	0.653	.....	0.700	0.590	.....	.....	.....	10.29	142	141	146
	Hoover	500	30	2.46	....	0.135	.....	.....	.....	.....	.....	.....	11.44	104	104	118
		1000		3.08	....	0.233	.....	.....	.....	.....	.....	.....	10.08	135	131	137
		1500		3.82	....	0.334	.....	.....	.....	.....	.....	.....	11.28	127	126	143
		2000		4.32	....	0.468	.....	.....	.....	.....	.....	.....	10.46	131	130	136
		2500		4.68	....	0.554	.....	.....	.....	.....	.....	.....	10.45	137	137	144
		3000		5.11	....	0.671	.....	.....	.....	.....	.....	.....	10.40	137	136	143
[b]No. 4—10851 1000° C—W	Special	3000	30	3.05	3.10	0.198	.....	.....	.....	.....	.....	.....	12.0	405	404	480
			20	3.07	3.11	0.211	.....	.....	.....	0.032	0.415	0.212	11.44	398	396	451
			10	3.05	3.01	0.188	.....	.....	.....	0.028	0.394	0.191	12.47	405	404	510
			0	3.07	3.08	0.193	.....	.....	.....	0.022	0.390	0.189	12.47	398	396	495
No. 12—4358	Hoover	3000	30	4.19	4.21	0.437	.....	.....	.....	.....	.....	.....	10.46	209	208	219
				4.17	4.20	0.427	.....	.....	.....	.....	.....	.....	10.63	210	210	224
				4.14	4.21	0.437	.....	.....	.....	.....	.....	.....	10.24	213	213	218
				4.17	4.20	0.437	.....	.....	.....	.....	.....	.....	10.39	211	210	219
[b]No. 12—4358 1000° C—W	Hoover	3000	30	2.54	2.41	0.067	.....	0.304	0.099	.....	.....	.....	23.06	614	605	1415
	Special		20	2.70	2.78	0.117	.....	.....	.....	0.030	0.371	0.142	15.72	521	512	816
	Special		0	2.89	2.80	0.138	.....	.....	.....	0.020	0.366	0.131	15.34	452	447	690

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[1] Columns 8 and 11 show readings between electric contact and 40-lb. initial load; Columns 9 and 12 show readings between 40-lb. initia load and full load; Columns 10 and 13 show readings between 40-lb. initial load and final 40-lb. load after pressure is released.

[a] These test pieces only $\frac{1}{4}$ in. thick.

[b] Pieces marked 1000° C—W were water-quenched after heating to 1000° C

TABLE II.—TABULATION OF MEASUREMENTS AND COMPUTATIONS FOR ALL CROSS-SECTIONS—*Continued.*

Designation.	Ball Used.	Load kg.	Held at Full Load, seconds.	Diameter of Impression, mm., by		Depth of Impression, mm.							Computed Diameter of Sphere which Fits the Impression.	Hardness Number as Computed from:		
				Instrument, Fig. 3.	Microscope.	Instrument, Fig. 3.	Olsen Gage.[1]			Amsler Gage.[1]				True Area.	Assumed 10-mm. Impression.	
							40-lb. Initial.	Full Load.	40-lb. Final.	40-lb. Initial.	Full Load.	40-lb. Final.			Diameter, Col. 5.	Depth, Col. 7.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
						STEEL AND IRON.										
No. 6—9946	Hoover	3000	30	4.67	....	0.549	.....	.....	.....	.....	.....	.....	10.39	166	165	186
				4.65	....	0.561	.....	.....	.....	.....	.....	.....	10.14	164	163	170
				4.70	....	0.599	.....	.....	.....	.....	.....	.....	10.33	154	154	159
[b]No. 6—9946 1000° C—W	Special	3000	30	2.77	2.79	0.136	.....	.....	.....	0.015	0.380	0.160	14.44	485	481	702
			20	2.74	2.79	0.131	.....	.....	.....	0.014	0.342	0.141	14.35	505	498	729
			10	2.69	2.73	0.131	.....	.....	.....	0.031	0.371	0.141	14.46	522	516	729
			0	2.84	2.70	0.128	.....	.....	.....	0.016	0.361	0.139	15.68	470	463	746
No. 4—10966	Hoover	3000	30	4.47	4.50	0.501	.....	0.587	0.454	.....	.....	.....	10.46	182	181	191
				4.39	4.41	0.486	.....	0.560	0.425	.....	.....	.....	10.39	189	186	193
				4.36	4.49	0.482	.....	0.585	0.459	.....	.....	.....	10.36	191	191	198
[b]No. 4—10966 1000° C—W	Special	3000	0	2.49	2.58	0.116	0.006	0.311	0.105	.....	.....	.....	12.46	612	605	828
			10	2.44	2.59	0.112	0.007	0.298	0.098	.....	.....	.....	13.3	639	632	855
			20	2.54	2.60	0.116	0.016	0.306	0.095	.....	.....	.....	14.07	587	572	828
			30	2.54	2.60	0.116	0.009	0.306	0.106	.....	.....	.....	14.07	587	572	828
MKD—455	Hoover	3000	30	3.41	3.48	0.264	.....	.....	.....	.....	.....	.....	11.26	322	319	361
		3000		3.43	3.48	0.264	.....	.....	.....	.....	.....	.....	11.41	318	315	363
		3000		3.43	3.50	0.265	.....	.....	.....	.....	.....	.....	11.37	318	315	362
		3000		3.40	3.49	0.259	.....	.....	.....	.....	.....	.....	11.44	322	321	368
		500		1.98	....	0.077	0.014	0.121	0.067	.....	.....	.....	12.87	...	...	...
		1000		2.19	....	0.097	0.000	0.178	0.079	.....	.....	.....	12.47	264	264	329
		1500		2.57	....	0.135	0.002	0.235	0.107	.....	.....	.....	12.31	288	282	357
		2000		2.98	....	0.183	0.001	0.300	0.141	.....	.....	.....	12.28	284	282	364
		2500		3.20	....	0.214	0.012	0.352	0.187	.....	.....	.....	12.17	306	295	372
[b]MKD—455 1000° C—W	Special	3000	30	2.54	2.45	0.089	0.008	0.292	0.078	.....	.....	.....	18.29	590	582	1075
			20	2.54	2.38	0.076	0.010	0.281	0.069	.....	.....	.....	21.28	590	582	1255
			10	2.54	2.50	0.075	0.007	0.286	0.065	.....	.....	.....	21.47	593	582	1272
			0	2.51	2.44	0.074	0.013	0.292	0.074	.....	.....	.....	21.37	604	596	1290
	Hoover	500	30	0.915	....	0.008	0.011	0.071	0.011	.....	.....	.....	27.60	760	758	2080
		1000		1.52	....	0.017	0.011	0.127	0.021	.....	.....	.....	33.72	555	531	1650
		1500		1.86	....	0.032	0.008	0.162	0.031	.....	.....	.....	27.33	550	545	1490
		2000		2.06	....	0.046	0.010	0.202	0.042	.....	.....	.....	23.15	600	593	1400
		2500		2.39	....	0.061	0.009	0.241	0.053	.....	.....	.....	23.46	556	548	1300
Gray C. I.	Hoover	500	30	2.18	2.00	0.084	.....	.....	.....	.....	0.124	0.093	14.28	132	132	189
		1000		2.74	2.80	0.159	.....	.....	.....	.....	0.226	0.154	11.96	167	165	200
		1500		3.05	3.00	0.198	.....	.....	.....	.....	0.274	0.224	12.02	200	201	241
		2000		3.61	3.40	0.277	.....	.....	.....	.....	0.440	0.354	11.23	233	231	262
		2500		3.64	3.70	0.303	.....	.....	.....	.....	0.538	0.410	12.16	190	185	230
		3000		4.42	4.20	0.415	.....	.....	.....	.....	0.340	0.259	12.09	190	189	230

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[1] Columns 8 and 11 show readings between electric contact and 40-lb. initial load; Columns 9 and 12 show readings between 40-lb. initial load and full load; Columns 10 and 13 show readings between 40-lb. initial load and final 40-lb. load after pressure is released.

[b] Pieces marked 1000° C—W were water-quenched after heating to 1000° C.

on a line connecting the last points of contact between the ball and the metal at the edges of the hole. Typical curves are shown in Figs. 4 and 5.

The results of these measurements are shown in the columns of Table II. Most of the columns in this table are self-explanatory. Columns 5 and 6 give the diameter of the impression, as measured in two ways, Column 5 being that obtained from the measurements made by the instrument, Fig. 3, and 6 being the same diameter as measured by the microscope. Column 7 gives the depth as taken from the measurements by the instrument, Fig. 3. Columns 8, 9 and 10 for the Olsen, and 11, 12, and 13 for the Amsler, are the corresponding depth-gage readings. Columns 8 and 11 show the increment of the gage reading between electric contact and the initial 40-lb. load. Columns 9 and 12 give the increment in the gage readings between the initial 40-lb. load and full load. Columns 10 and 13 give the increment in the gage readings between the initial 40-lb. load and the final 40-lb. load after the impression had been made. The impression within the body of the hole was in all cases found to be symmetrical and spherical as nearly as was measurable. Since this was true, it was possible to take the depth t from Column 7, and the diameter d from Column 5, and compute the diameter, D_1, of the equivalent sphere which would fit the impression left by the ball, from the formula

$$D_1 = \frac{d^2}{4t} + t.$$

These diameters D_1 have been recorded in Column 14 of the table, and it will be noted that in some cases the diameter of this equivalent sphere is as great as 33 mm., or nearly $3\frac{1}{2}$ times the diameter of the ball which made the impression.

Fig. 6 illustrates the three bases for the hardness numbers shown in Columns 15 to 17, Table II. The number given in Column 15 was found by dividing the load by the true area of impression or that area generated by revolving the curve *AOA* about a vertical axis through *O*. It is felt that this is as nearly a rational value for the Brinell hardness number as can be obtained. The number in Column 16 was found by dividing the load by the area generated by revolving the curve *BOB* about a vertical axis through *O*. In this case, from the diameter of the impression *BB*, the area of contact is computed as the zone of a 10-mm. sphere. The number in Column 17 was computed from the area generated by revolving curve *COC* about a vertical axis through *O*, on the assumption that the area of contact is a zone of a 10-mm. sphere, with a depth equal to that actually measured by the instrument. A glance at the sketch will show that the area *BOB* is much more nearly equal to *AOA* than is the area *COC*, hence the number given in Column 16 must be much nearer to the true-area hardness than that in Column 17. The numbers in Columns 16 and 17 are those read from ordinary Brinell tables using the diameter and depth, respectively, as obtained from measurements made by the instrument Fig. 3.

In Fig. 7 are given curves resulting from plotting the actual depths as taken from the instrument readings in Column 5 against the readings taken with the Olsen depth gage under a 3000-kg. load. It will be noted that the average readings for the full load appear to be greater than the true depths by a fairly constant amount down to an actual depth of 0.4 to 0.5 mm., and that for smaller depths the difference becomes greater. This excess of the full-load reading over the true depth is doubtless due to the compression under the load in the ball and in the shank of the apparatus below the effective point of contact with the gage, and this appears to increase as the area of contact becomes smaller. The readings of the depth gage taken after the load has been released to 40 lb. are usually smaller than the true depths, but this difference decreases as the actual depth decreases. This discrepancy is due to two causes:

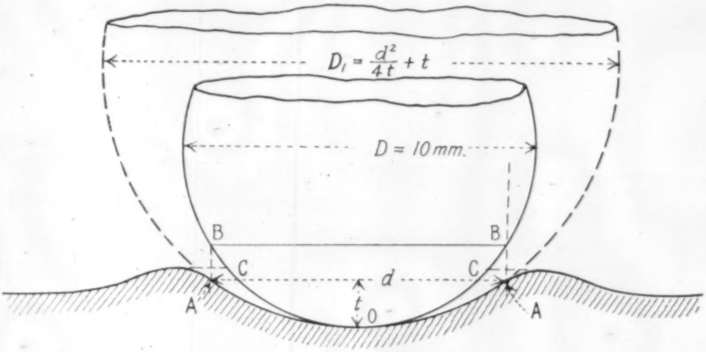

FIG. 6.—Illustrating the Three Bases for Hardness Number Computation.

1. The depth caused by the initial reading of 40 lb. is not included in the reading of the gage; and

2. The flow of the metal around the hole causes in many cases a swelling which is not measured by the depth gage.

It will be noted that the full-load readings are on the whole as consistent as the gage readings under 40 lb. at the end of the test.

Fig. 8 shows the true diameters and the microscope diameters plotted in a manner similar to that for the depths. All diameters for all loads are plotted here, however, rather than one loading only, and the consequent number of points is greater. The table in this figure shows the maximum variation from the mean in percentages. These variations lie about equally above and below the true depth and indicate no tendency in any one direction.

In Fig. 9, the hardness numbers as shown in Columns 15, 16 and 17, Table II, for the 3000-kg. loadings have been plotted against the depth of impression, as taken from Column 7. Readings from this diagram, consequently, give the comparative hardness numbers of the same piece of metal as computed on the three assumptions.[1] It will be noted that for low hardness numbers, not over 150, there is very little difference between the three methods of computation, but that as the depth of impression decreases, the hardness number computed from the depth of impression (and with the impression assumed

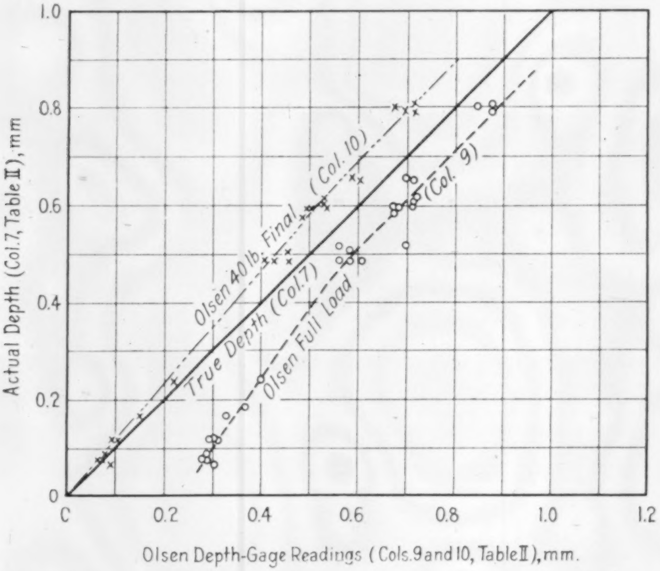

FIG. 7.—Comparing True Depth and Olsen Depth-Gage Readings for 3000-kg. Load.

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[1] Since the coordinates are hardness numbers and the actual depths, the curve representing the hardness as computed from the depth is the only one on which all the points shown in the table can be expected to fall. The other curves are, of necessity, *average lines* and the hardness numbers shown in the table would be expected to fall on either side of the respective curves since neither diameter nor true area varies exactly as the depth.

to be the zone of a 10-mm. sphere) increases very much more rapidly than the hardness number as computed from the true area of the impression. Except for the extremely high hardness numbers, the number as computed from the diameter with the impression assumed a sphere of 10-mm. diameter is almost identical with the true-area hardness number, never varying even on the very hard metals by more than 8 or 10 units of hardness. Curves are also plotted showing the hardness numbers computed from the full-load readings of both the Olsen and Amsler gages. These curves are quite similar in shape and both lie considerably below the true-area hardness curve, as would be expected, since the depth-gage readings taken at full load are greater than the true depths, due to compression in the ball and the shank of the gage and to the resilience of the test piece.

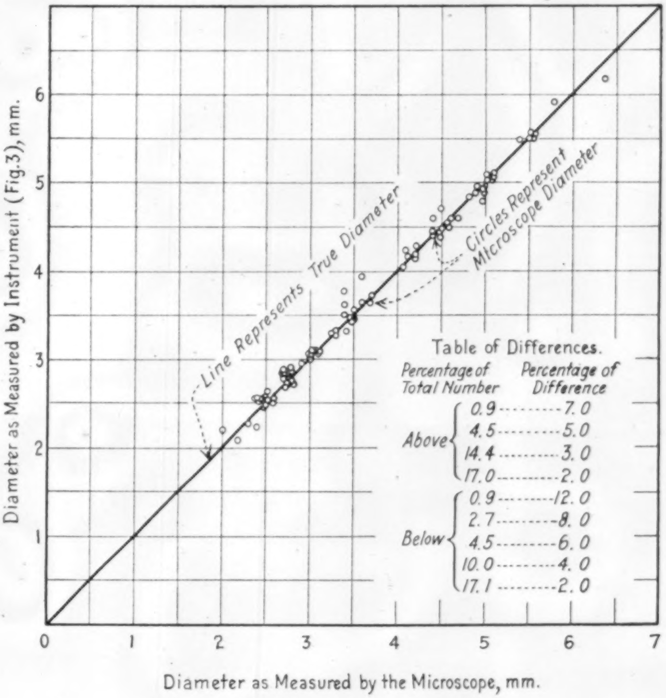

FIG. 8.—Comparing Diameter Measurements by Microscope with those by the Instrument, Fig. 3. Diameters for all Loads are Plotted.

In Fig. 9 there is also plotted a similar set of curves for 500-kg. loadings and the Olsen gage. The full-load depth-gage curve has been shown here for the Olsen gage only, since we have insufficient readings with the Amsler at this load to justify a curve. It will be noted that the curves for the 500-kg. loads are similar in shape to those for the 3000-kg. loads and that the discrepancy between the methods of computing hardness numbers becomes important at much lower hardness numbers than in the case of the 3000-kg. loadings.

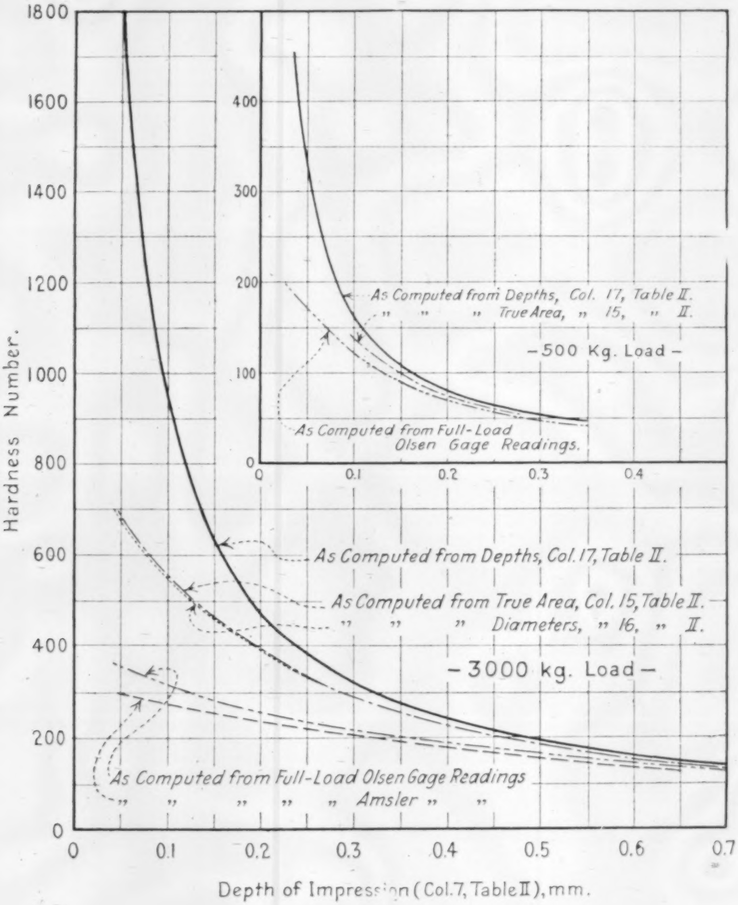

FIG. 9.—Hardness on Various Assumptions Plotted Against Depth of Impression, for 3000 and 500-kg. Load.

Impression assumed at a zone of a 10-mm. sphere except for true area curve.

Both these sets of curves indicate that there is some sort of constant relation between the hardness numbers as computed on the various assumptions and that it is possible to reduce one to the other. Fig. 10 shows curves which reduce 3000-kg. full-load depth-gage readings for both the Olsen and Amsler gages to true-area hardness numbers Here the hardness numbers, as read from the true-area hardness curve in Fig. 9, have been plotted against the full-load depth-gage readings as taken from the average curve of Fig. 7 for the Olsen gage, and a similar curve for the Amsler gage, which is not shown. With these curves it is possible to read the true-area hardness numbers from the full-load reading of the Olsen or Amsler depth gages. These curves, of course, are average curves, and the true-area hardness numbers would be expected to fall on either side of the curve if accurately computed, but in this investigation never with more than 10 per cent error. For purposes of comparison there is also shown in Fig. 10 a curve of hardness numbers as computed from the full-load depth-gage readings, assuming the impression to be the zone of a 10-mm. sphere, which seems to be a common method of using the depth-gage readings. It will be noted that these hardness numbers are much too low.

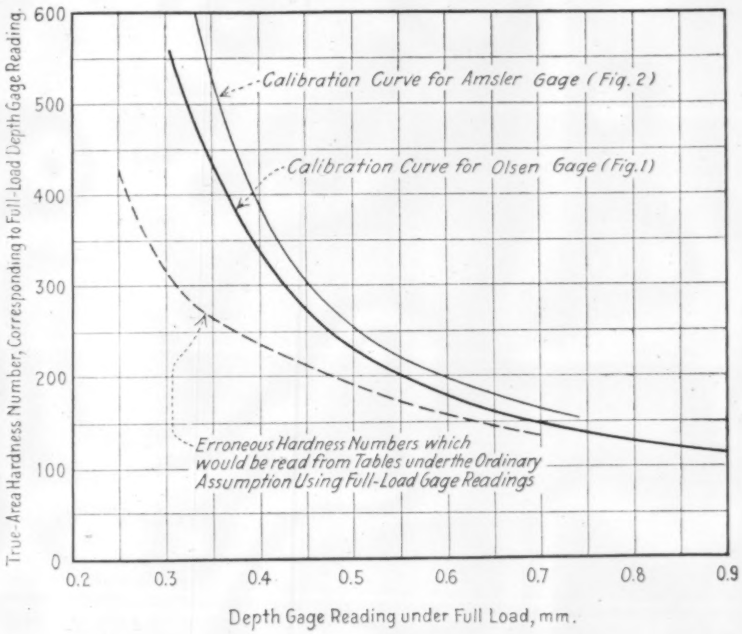

FIG. 10.—Calibration Curves for Two Depth Gages, for 3000-kg. Load.

True-area hardness numbers may be read from these curves from full-load depth-gage readings.

DEPTH GAGE *versus* DIAMETER READINGS.

From the data in Table II and from the curves in Fig. 9, it can hardly be maintained with justification that from the standpoint of accuracy the depth-gage readings are as satisfactory as the diameter readings for measuring hardness. This is so, first, because the depth gage must be calibrated and the hardness number then becomes simply an empirical thing, whereas the hardness number as computed from the diameter of impression is very close to the true-area hardness number throughout, and hence is satisfactory without the application of arbitrary factors. Again, each individual gage must be calibrated for each loading for which it is used and also for

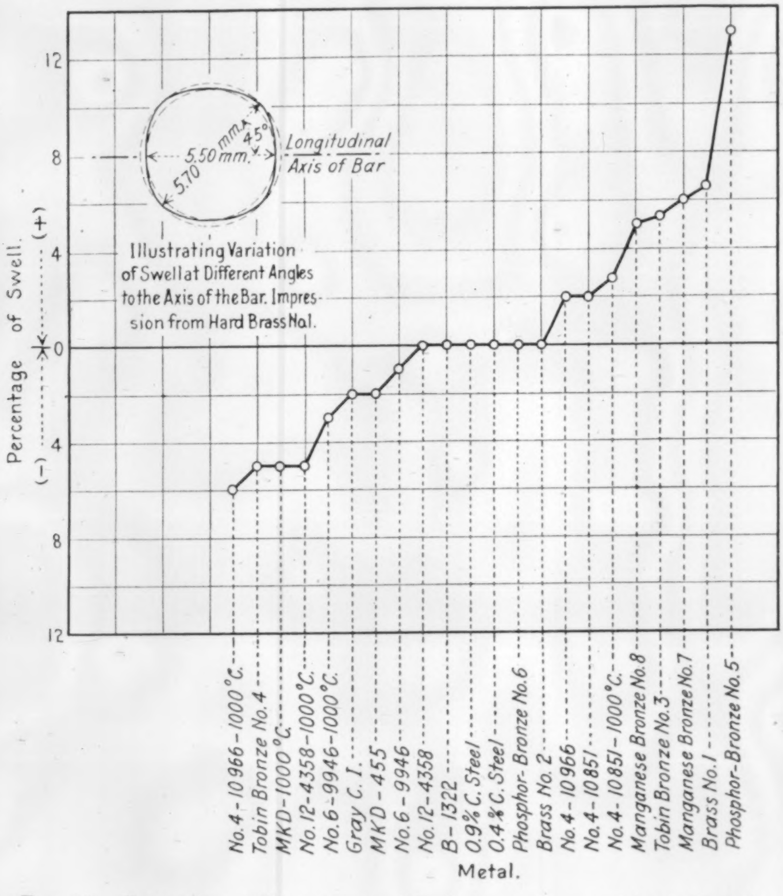

FIG. 11.—Comparison of Percentages of Swell for the Several Metals Tested.

balls of different grades of hardness, such as the Hoover balls and the special balls used in the investigation. All these factors tend to introduce errors into the final hardness numbers as computed from depth-gage readings.

On the other hand, the depth-gage readings may be taken much more quickly than diameter readings with the microscope, and apparently give hardness numbers which do not vary more than 10 per cent from the true hardness and usually are considerably closer than this. Again, in the case of the very hard metals, the outline of the impression becomes so indistinct that it cannot be measured by the microscope. Certain laborious methods have been employed in the past to make this outline more distinct, such as polishing the specimen, etching the ball, etc. The full-load depth-gage readings are not open to this difficulty for the hard metals, and consequently would appear to have an advantage over the diameter readings for the hard metals. It is, in fact, possible to measure hardness by the depth gage where the outline of the hole is not sufficiently defined to warrant taking a diameter measurement at all. A glance at Fig. 7 and Table II will verify this.

Since there is no apparent superiority of the depth-gage readings at 40 lb. after the impression has been made over the full-load readings, and considerable more trouble is involved in obtaining them, these readings have not been used for computations.

Since the hardness number, as computed from the true area, is almost identical with that computed from the diameter of the impression, assuming this impression to be a zone of a 10-mm. sphere, it is only necessary in calibrating a depth gage for use, to plot the latter hardness numbers against the full-load depth-gage readings throughout the range of hardness in which the gage is to be used. An average line through these points is the calibration curve for the gage, and from this line hardness numbers closely approximating the true-area hardness numbers may be read from the full-load depth-gage reading.

EFFECT OF SWELL AT EDGE OF IMPRESSION.

In most cases the effect of the upsetting of the metal at the edges of the impression is evident in the raising of a ridge or swell above the original surface of the test piece, but this is not always true. The extreme point of contact between the ball and the metal at the edge of the impression is sometimes above and sometimes below the original surface. This is illustrated in Fig. 11, in which this distance above or below is represented as a percentage of the depth of the impression. This percentage is found to vary in different impressions on the same metal and in some cases in different directions in the same impression. Thus, in hard brass No. 1, there was a most marked variation for the same impression, the swell on a line at 45 deg. with the axis of the bar being much greater than that in either the longitudinal or transverse direction. The effect on this metal was sufficiently marked to give the impression a rectangular appearance, even to the naked eye. (See Fig. 11.) The body of the impression even in this case was found to be perfectly regular and spherical as determined by measurements taken along the 45-deg. line as well as on the lateral and transverse axes of the bar.

This upsetting of the metal beyond the edge of the impression raises the following questions:

(*a*) Do the points of contact of the depth gage lie close enough to the ball to record any of the effect of the swell, and if so, how much?

(*b*) Could a depth gage be designed to measure all the swell?

(*c*) What effect has the swell on the measurement of diameter with the microscope?

(*d*) Does the amount of the swell have any relation to hardness, ductility or other properties of the metal?

(*e*) What should be the size of the test piece?

In no case does the effect of the swell extend more than 6 mm. from the center of the impression and the top of the ridge is only about 0.2 mm. back from the extreme point of contact of the ball and metal. To include this ridge in the measurement of the depth, the points of contact of the gage would need to be very close to the ball at all times, which could only be accomplished if they were capable of lateral motion. In neither of the gages used in this investigation were the points of contact close enough to record any of the effect of the swell.

In measuring diameter with the microscope an average of diameters measured in different directions should be used.

A comparison of the hardness numbers with the percentages of swell for the various metals shows no uniform relation. Possibly there is a closer relation between the swell and the ductility or the toughness.

In no case did any disturbance of the surface of the test piece extend as far as $\frac{1}{4}$ in. from the center of the ball. One-half inch would seem to be sufficient for the width of a test piece or for the distance between impressions.

EFFECT OF VARIABLE LOAD.

Tests were made on eight samples with loads varying from 500 to 3000 kg. by increments of 500 kg. These are listed in Table II and the relation of the hardness numbers and corresponding diameters of the spherical impressions is shown by the curves in Fig. 12 for the four most consistent cases. These curves seem to indicate that the hardness numbers, to a certain extent, vary inversely with the diameter of the sphere. They also indicate that there is a certain load which will give a maximum hardness number, as some writers have maintained, that this load varies with the metal and occurs when the diameter of the spherical impression is a minimum. It is also evident that the hardness number may vary as much as 20 per cent with different loads.

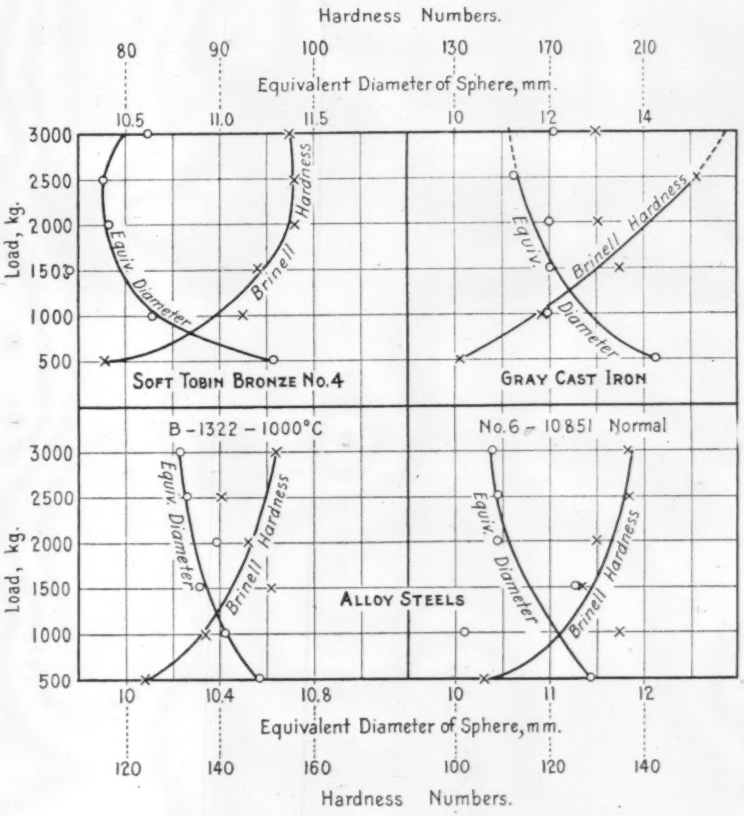

FIG. 12.—Showing the Variations of the Equivalent Diameter of Impression and Hardness Numbers with the Load.

EFFECT OF TIME OF LOADING.

It will be seen by reference to Column 4, in Table II, that a few tests were made by reducing below the standard 30 seconds the time during which the load was held on the test piece, after it attained its maximum. The time during which the load is held at its maximum seems to have no appreciable effect on the hardness number. On the other hand, great care is required in applying the load so that the inertia of the moving parts of the machine will not cause an overload. In a few tests in which the load was applied rapidly the effect was very noticeable, but these are not included in the table.

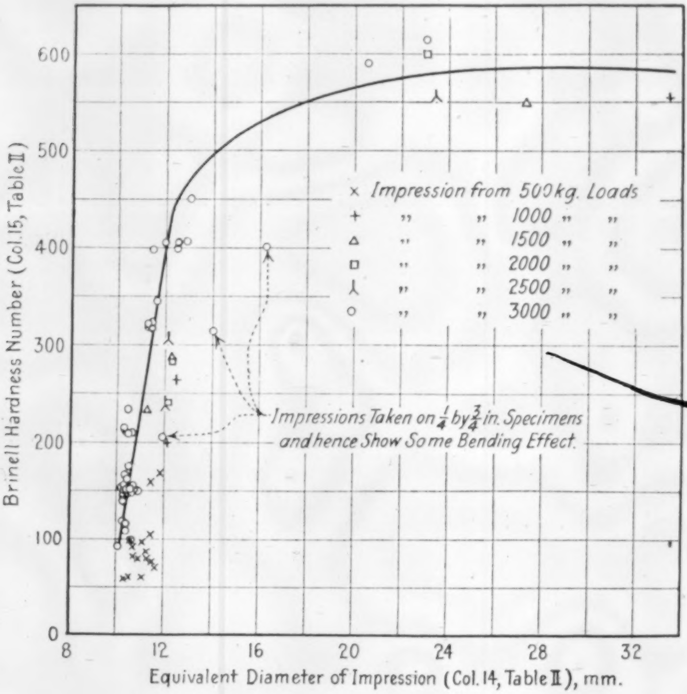

FIG. 13.—Showing the Relation Between Hardness and Distortion of the Brinell Ball (Hoover Ball).

RELATION OF HARDNESS NUMBER TO DIAMETER OF SPHERICAL IMPRESSION.

The relation of the hardness number to the diameter of the spherical impression is shown in Fig. 13. Most of the points plotted show the results obtained from the 3000-kg. load, but a few others were added, especially where data from the heavier load were meager. All the tests shown here were made with the Hoover ball, those made with the "special" ball being omitted. It will be seen that the curve drawn from these data is approximately of the form of the characteristic stress-strain curve, having, as the hardness number increases, a uniform slope up to about 400 or 450, and that the diameter increases very rapidly from that point as the number approaches 600. It would seem from this curve that 600 is about the limit of hardness that can be accurately determined with the ordinary Brinell ball. The fact previously mentioned, that the diameter is greater under the lighter loads, is brought out in this figure.

CONCLUSIONS.

1. The true area of the surface of the indentation is that of a zone of a sphere whose diameter is greater than 10 mm.
2. The true area is always less than that computed by using the measured diameter and greater than that computed by using the measured depth of the impression, assuming the shape to be that of a sphere 10 mm. in diameter.
3. The area computed from the measured diameter is always very nearly equal to the true area, while that computed from the measured depth may be very much smaller than the true area, in some hard steels less than one-half that area.
4. From (3) it follows that the hardness numbers computed from measured diameters alone are practically correct, while those computed from measured depths alone are greater than the true-area hardness numbers and may be greatly in error.
5. Hardness numbers obtained by reading the diameter of impression with an ordinary Brinell microscope were found, in extreme cases, to be in error by about 12 per cent.
6. Hardness numbers obtained by using a depth gage and the ordinary tables for depth are incorrect, especially so with hard materials.
7. A depth gage may be calibrated so that readings may be used to find hardness numbers with a maximum error of about 10 per cent.
8. There is no advantage in releasing the load to the initial load before reading the depth gage, as such reading does not give the actual depth of the zone of contact and calibration would be required, as when the reading is taken under full load.
9. The depth gages used do not record the depth of the swell around the impression as the point of contact is too far away.

10. In some metals the diameter of the surface impression varies perceptibly in different directions and an average should be used in determining the hardness number.

11. Since the effect of the swell was found in no case to extend more than $\frac{1}{4}$ in. from the center of the ball, the width of the surface of the test piece of $\frac{1}{2}$ in. seems to be sufficient.

12. The hardness number may vary as much as 20 per cent under loads varying from 500 to 3000 kg.

13. The load should be applied very slowly as it reaches its maximum, as a rapid application greatly reduces the apparent hardness number.

14. The length of time during which the load is held at its maximum has no appreciable effect on the hardness number.

DISCUSSION.

MR. HERMAN A. HOLZ (*presented in written form*).—The authors have discussed some of the difficulties encountered in measuring both the depths and diameters of the ball indentations produced in the Brinell test, and their conclusions seem to point out that, at least for routine work, the diameter measurement is quite accurate and the more satisfactory of the two methods. This is borne out by the practical experience of many industrial laboratories in this country and abroad. **Mr. Holz.**

There are only a few points in this paper that I desire to discuss. In the case of very hard metals when the outline of the impression becomes very small, and the same is, of course, true when a very small ball and small pressure (say 30 kg. on a 1-mm. ball) is used, such as in hardness investigations of thin sheets, it will be found quite convenient to measure the diameter of the impression on the ground glass of the camera attached to a metallurgical microscope. After the actual rate of magnification has been carefully determined by means of a stage micrometer divided to 0.001 mm., the specimen is put on the stage of the microscope and the image of the indentation produced in the camera can then be accurately and conveniently measured. I believe that in such cases the diameter measurement will be much more accurate than the depth measurement of the same indentation.

Referring to some of the conclusions, the ridge formation around the indentation mentioned in Conclusion No. 9 is ignored with purpose in the construction of the various depth gages, as the variations encountered would have the tendency to cause very erratic indications in such depth measurements. The point of contact is purposely removed quite a distance from the ball, so that the depth reading will show as accurately as possible the difference between the original surface position of the ball, the surface always considered perfectly straight and smooth, and its position at the bottom of the indentation.

Regarding Conclusion No. 11, there is no connection between the size of the ridge formation around the indentation and the zone of metal permanently affected by the Brinell test. While this permanently affected zone differs in size with the various metals and alloys, thus making it impossible to state definitely the minimum width of specimen permissible in all cases, I have reasons to believe that a specimen of $\frac{1}{2}$-in. width will be found too narrow in most cases, in testing steel, and entirely out of the question in testing non-ferrous metals.

Mr. Holz. The point raised in Conclusion No. 12, which is quite correct and probably one of the most important drawbacks of the Brinell method, can be successfully eliminated in all practical testing work by chosing the load thirty times the square of the diameter of the ball. On smaller sections which cannot be satisfactorily tested at 3000-kg. pressure on a 10-mm. ball, a load of 750 kg. on a 5-mm. ball will give satisfactory results.

The statements contained in Conclusions Nos. 13 and 14 are somewhat too general. With the great variations present in the plastic properties of the metals and alloys it is quite impossible to cover them all with a definite statement as to the plastic flow of the metal under pressure. It seems that the variations produced by a difference in the time rate of load application are, in some metals, a source of much larger error than variations in the period of exposure of the metal to the maximum load. Unfortunately, the more important point of the two, the time rate of load application, has not yet been covered by standard specifications, although it would not be very difficult to standardize this. Guillery[1] suggested to eliminate the variations which he found at different speeds of increasing the pressure, his experiments showing differences of 12 and 15 per cent, by means of a specially constructed spring attachment to the cross-arm above the automatic valve release mechanism of the Brinell machine. He states that by means of his attachment he was enabled to carry out 600 Brinell tests per hour, each test requiring 6 seconds. This high speed of testing may have been necessary during the war, but there are very few plants in this country that require it during peace times. The variation in test results produced by different speeds in reaching the maximum test pressure can be eliminated by standardization better than by mechanical means.

The period of exposure of the specimen to the standard test pressure which has already been standardized to 30 seconds on iron and steel and 60 seconds on non-ferrous metals has no appreciable effect on some metals and a very considerable effect on others. As mentioned above, it is quite impossible to generalize, and the best rule to follow is to apply the pressure for the standard period. Only by adhering to the standardized testing rules and by standardizing those points of technique which still produce variations between hardness tests at different plants can the Brinell test give full satisfaction to its many users in all parts of the world.

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[1] Guillery, "L'Essai de Dureté des Metanse à la Bille Brinell;" *Comptes Rendus*, October 8, 1917.

PHYSICAL PROPERTIES OF SUBGRADE MATERIALS.

By J. R. Boyd.[1]

Last year at the annual meeting of the Society a paper entitled "Tests for Soils with Relation to Their Use in the Subgrade of Highways" was presented jointly by A. T. Goldbeck and F. H. Jackson[2] of the U. S. Bureau of Public Roads. The primary purpose of that paper was to present such tests for determining the physical properties of subgrade materials as had at that time been developed, no attempt being made however to draw definite conclusions from the data obtained from these tests. During the past year it has seemed advisable in some instances to materially change the methods of testing, consequently the complete revised procedure will be presented in this paper. An attempt will also be made to correlate the data so far obtained and to draw any general conclusions which may seem warranted.

Procedure for Testing Subgrade Materials.

Preparation of Soil Samples.—The sample as received from the field is broken up in a mortar by means of a rubber-covered pestle, care being taken not to break any of the rock fragments, and passed through a ¼-in. screen. That portion of the sample which passes the ¼-in. screen is pulverized by passing between rubber rolls[3] and is then passed through a 10-mesh sieve. Only that portion of the sample which passes the 10-mesh sieve is used in making the following tests.

Mechanical Analysis.—By the method of quartering, a sample weighing approximately 25 g. is selected from the soil prepared as described above. This sample is then dried in an oven to constant weight at a temperature not exceeding 100° C. and is allowed to cool in a desiccator. The cooled sample is then weighed and placed in a beaker with approximately 500 cc. of distilled water. This mixture is gradually brought up to the boiling point during a period of one hour and is allowed to simmer for an additional hour. After standing until cool, the material in the beaker is thoroughly brushed and dispersed with a stiff brush for 2 or 3 minutes and then allowed to stand for 8 minutes. The supernatant liquid is then decanted to a depth of 8 cm. from the surface of the liquid into a vessel having a capacity of about 10 liters. About 500 cc. of ammoniated water (concentration 1 : 500) is then added to the material remaining in the beaker and the brushing repeated as before. After again standing for 8 minutes, the supernatant liquid is decanted into the large vessel. This process is repeated until the supernatant liquid becomes clear after 8 minutes sedimentation. The sand and silt have now been separated from the clay and suspension clay, which are contained in the large vessel. The material in the beaker is transferred to an evaporating dish and dried to constant weight at a temperature not to exceed 100° C. (212° F.), cooled, and a mechanical analysis made, using the 20-mesh, 50-mesh, 100-mesh, and 200-mesh sieves. The material retained on each sieve is recorded as percentage of the original sample, and that which passes the 200-mesh sieve is recorded as the percentage of silt in the original sample.

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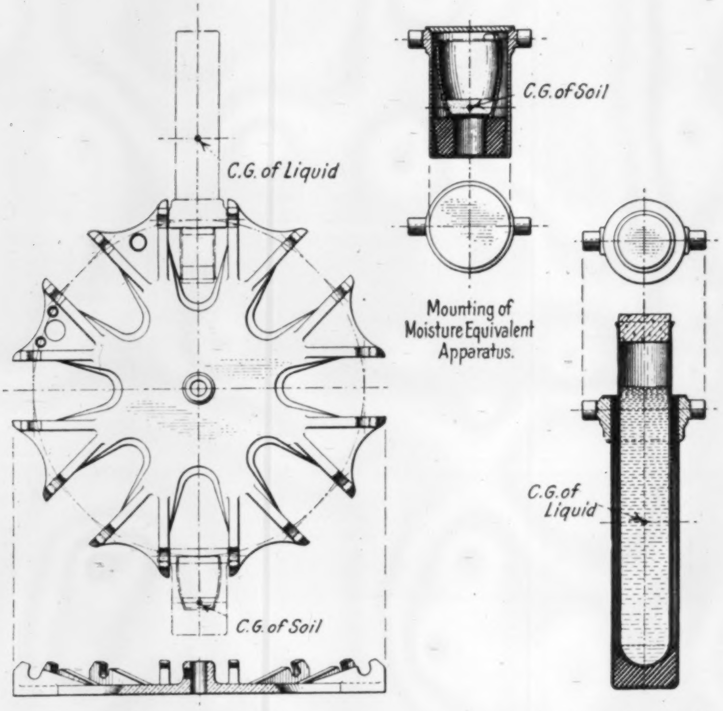
[1] Junior Assistant Testing Engineer, U. S. Bureau of Public Roads, Washington, D. C.

[2] *Proceedings*, Am. Soc. Test. Mats., Vol. 21, p. 1057 (1921).

[3] A clothes wringer is useful for this purpose.



Centrifuge Head.

Mounting of Centrifuge Tube.

FIG. 1.—Showing Centrifuge Head and Mounting of Centrifuge Tube and Moisture Equivalent Apparatus.

The volume of the liquid in the large vessel is now brought up to at least 10 liters by the addition of ammoniated water, and the vessel thoroughly shaken until all material is in suspension. Seventy cubic centimeters of the liquid are then siphoned from this vessel at a depth of about one-half the total depth of the liquid, into each of four centrifuge tubes. These tubes are then mounted in the centrifuge and run for one-half hour at a speed which for the diameter of the

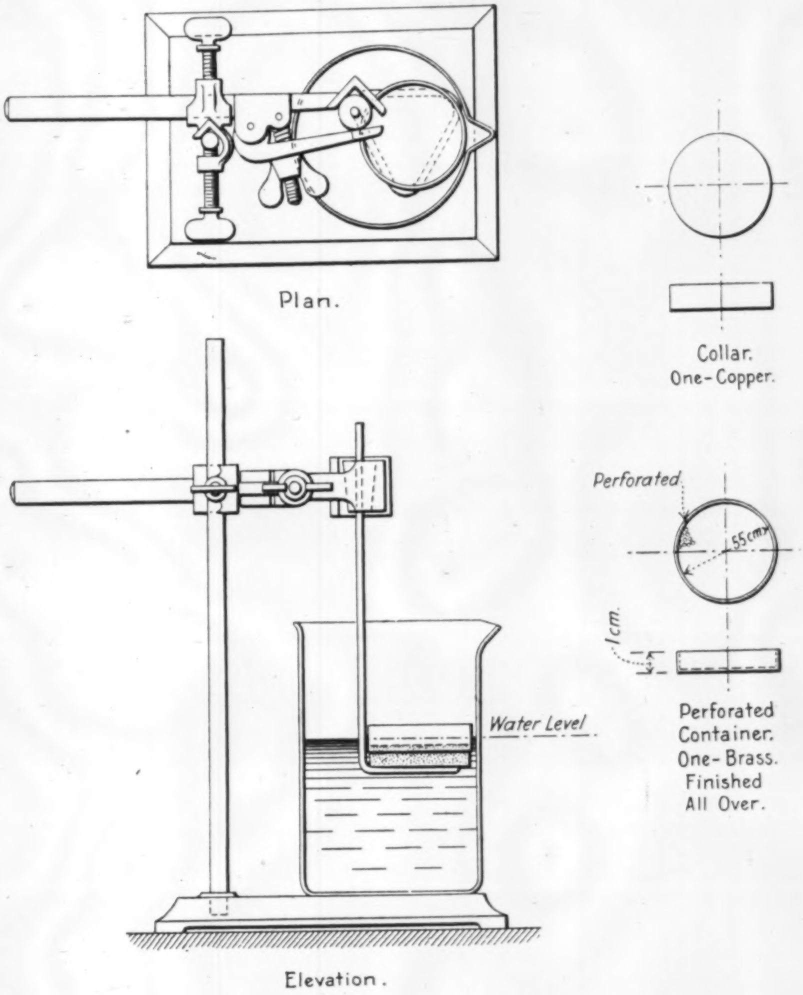

Plan.
Collar.
One-Copper.
Perforated
5.5cm
1cm.
Water Level
Perforated
Container.
One-Brass.
Finished
All Over.
Elevation.

FIG. 2.—Apparatus for Determining Water Capacity of Soils.

head used will exert a centrifugal force approximately 500 times the force of gravity. The mounting of the centrifuge tube is shown in Fig. 1. The material which has been thrown out of the liquid by centrifuging is classified as clay and that which remains in suspension as suspension clay. The solution containing the suspension clay is decanted, evaporated to dryness and the weight of the suspension clay is determined. The clay remaining in the tube is also dried and weighed.

The weight of suspension clay is found from the liquid in four tubes or 280 cc., consequently this weight must be multiplied by the factor obtained by dividing the total volume used by 280 cc. in order to obtain the total suspension clay in the original sample. The weight of clay is determined from the clay in one tube or 70 cc., therefore the total volume divided by 70 cc. gives the factor by which this weight should be multiplied to give the total clay in the original sample. The total weights of clay and suspension clay thus obtained are converted into percentages of the original sample.

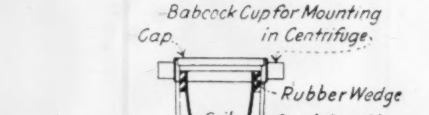


FIG. 3.—Apparatus for Determining Moisture Equivalent.

The determination of the percentage of suspension clay by this method will include any water-soluble material present which may be determined separately if desirable.

Water-holding Capacity.—The water-holding capacity of a soil may be considered as the maximum percentage of water which it is capable of retaining. The test for it is made in the laboratory in the following manner: A sample of the soil which has been prepared as described above is placed in a brass cylindrical box 1 cm. high and 5.5 cm. in diameter. The bottom of the box is perforated with 150 holes each $\frac{1}{32}$ in. in diameter. The top of the soil is then struck off by means of a fine silk thread, and after weighing is placed in a pan of water on a brass triangle, and submerged 5 mm. below the surface of the water for one hour. The surface water on the container only is then blotted off and the sample immediately weighed. The water-holding capacity is determined on the basis of the dry soil. This test is illustrated in Fig. 2.

Moisture Equivalent.—The "moisture equivalent" of a soil has been defined by Briggs and McLane[1] as the percentage of moisture which is retained by a soil when it is subjected to a centrifugal force equal to 1000 times the force of gravity. The test is made as follows: A 5-g. sample of the soil, prepared as described above, is placed in a Gooch crucible and allowed to take up water by capillarity until saturated. It is then placed in the damp closet and allowed to stand over night to insure even distribution of the moisture. The crucible is then placed in a Babcock cup containing a rubber stopper to serve as a cushion and provided with a hole sufficiently large to hold the water thrown out during centrifuging. The cup is provided with a brass cap to prevent evaporation. The sample is centrifuged for one hour

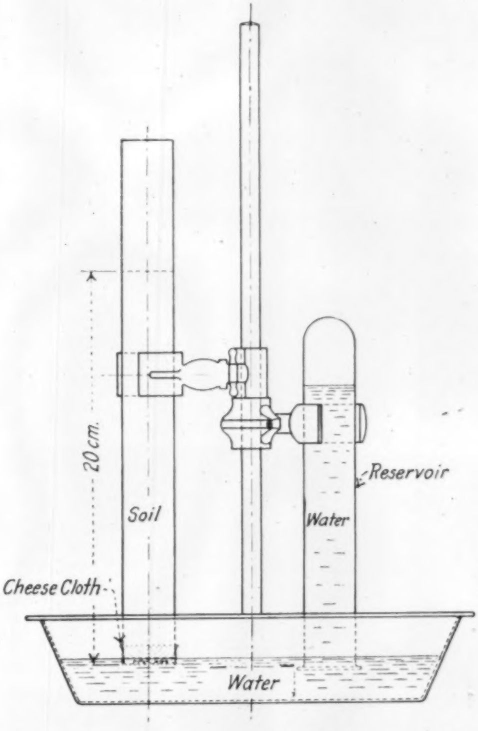


FIG. 4.—Apparatus for Determining Percentage Moisture by Vertical Capillarity.

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[1] U. S. Bureau of Soils *Bulletin No. 45.*

at a speed which, for the diameter of head used, will exert a centrifugal force approximately 1000 times the force of gravity. The mounting of the apparatus is shown in Figs. 1 and 3. Moisture equivalents are obtained by weighing the soil after centrifuging and then drying to constant weight and weighing again. The moisture equivalent is the percentage of moisture, based on the dry weight of the soil, which is retained after centrifuging.

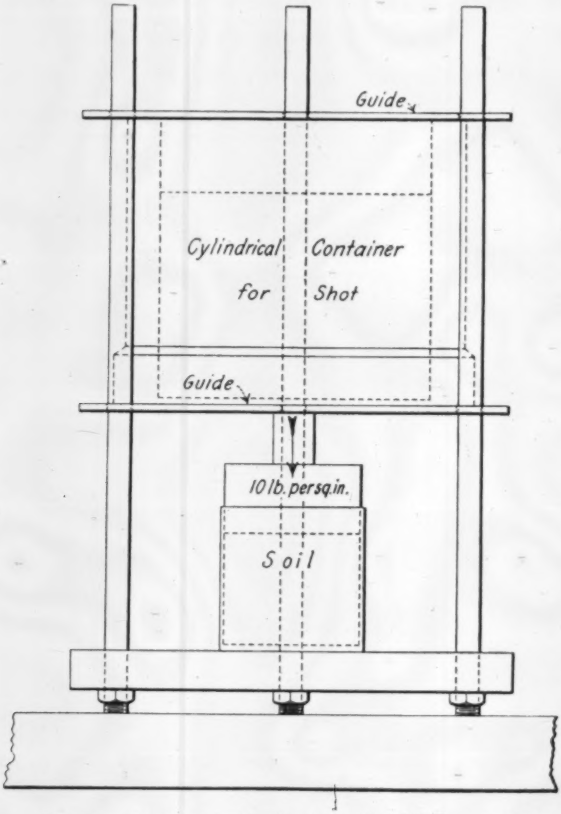


FIG. 5.—Apparatus for Applying Initial Pressure.

Vertical Capillarity.—This determination is made for the purpose of ascertaining the average percentage of water which will be lifted a distance of 20 cm. in a column of dry soil 25 mm. in diameter. It is of value for comparative purposes only and does not necessarily bear any relation either to the total capillary lift of the soil or the maximum percentage of water which it is capable of holding by capillary attraction. A sample of the soil prepared as described is poured loosely into a 25-mm. glass tube and the tube is jarred until a height of 20 cm. has been reached and no further settlement takes place. A piece of cheese cloth is fastened to the lower end of the tube to hold the soil in place. The lower end of the tube is then just immersed in water. When capillary water reaches the top of the soil column, the tube is weighed and the amount of water taken up by capillarity thus determined. This weight, expressed as the percentage of the dry weight of the soil, may be considered as the average percentage of moisture which will be taken up by capillarity under these conditions. This test is shown in Fig. 4.

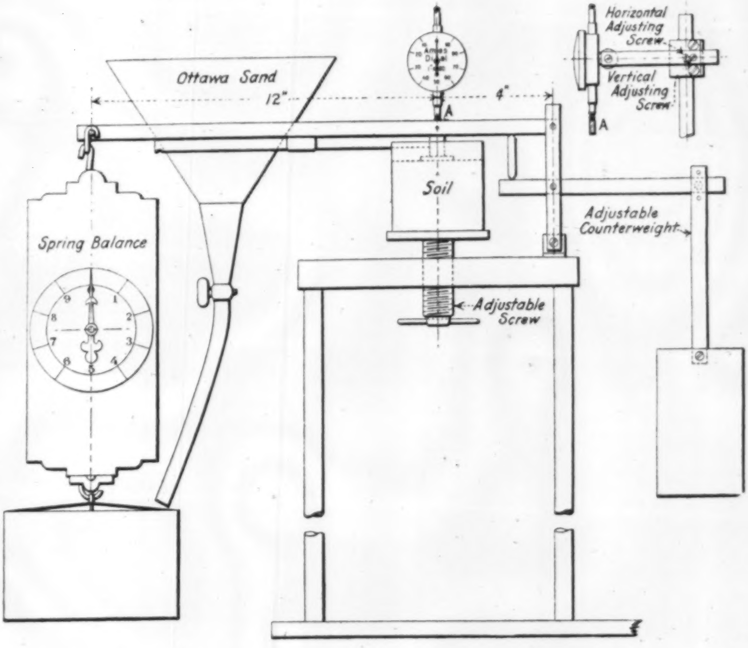

Horizontal Adjusting Screw
Vertical Adjusting Screw
A
Ames Dial
Ottawa Sand
12"
4"
A
Soil
Spring Balance
9
1
8
2
7
3
6
5
4
Adjustable Counterweight
Adjustable Screw

FIG. 6.—Apparatus for Determining Bearing Value of Soils.

Volumetric Change.—A sample of the soil passing a 10-mesh sieve is mixed with a given quantity of water and placed in a small flat cylindrical porcelain dish approximately 6 cm. in diameter and 1 cm. high, struck off level with a small trowel and weighed. The sample is then allowed to air dry and is weighed at frequent intervals until no further loss in weight is recorded. The percentage of the final volume in terms of the original volume is determined by filling with mercury the pan containing the dried soil sample. Knowing the volume of the pan and the volume of the mercury required to fill it after contraction of the soil has taken place, the percentage of contraction may be calculated. The volume of mercury in the container is controlled by means of a glass plate which is pressed down firmly over the top of the pan, thus squeezing out the excess.

Comparative Bearing Value.—The apparatus for determining the comparative bearing value of soils is shown in Figs. 5 and 6. The soil is prepared for testing by mixing the desired amount of water with the soil by hand. That is, the mixture is kneaded thoroughly for several minutes in order that complete distribution of the moisture may be obtained. The mixture is then covered with a pan and allowed to stand for about 15 minutes, after which it is subjected to an initial load of 10 lb. per sq. in. to insure uniformity of compaction (Fig. 5). Having applied the static load and having placed the 1-sq.-in. bearing block upon the soil, the container is raised by means of the adjusting screw (Fig. 6) until the horizontal beam has been carried vertically 0.1 in. The sand for applying the load is now released and simultaneous readings of load and penetration are made for 0.1-lb. increments, the maximum penetration used being 0.2 in. As the point of equilibrium of the system corresponds to a dial reading of zero, the beam is displaced 0.1 in. above the true horizontal position at the beginning of the test and 0.1 in. below at the end of the test. It has been found that the error introduced owing to this condition is negligible. Load readings as obtained from the spring balance must be multiplied by four, owing to the ratio of the lever arms. Check tests are run on each soil and from the average of these, the bearing value curve is plotted. For comparative purposes, the bearing value of the soil is taken as that load in pounds per square inch required to produce a penetration of 0.1 in. Figs. 14 and 15 are typical bearing value curves showing the method by which the comparative bearing value of different soils is obtained.

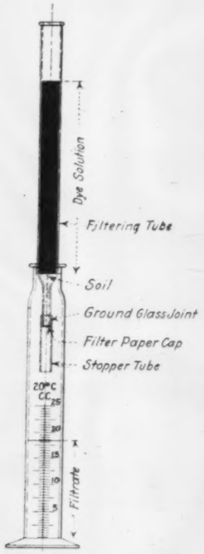
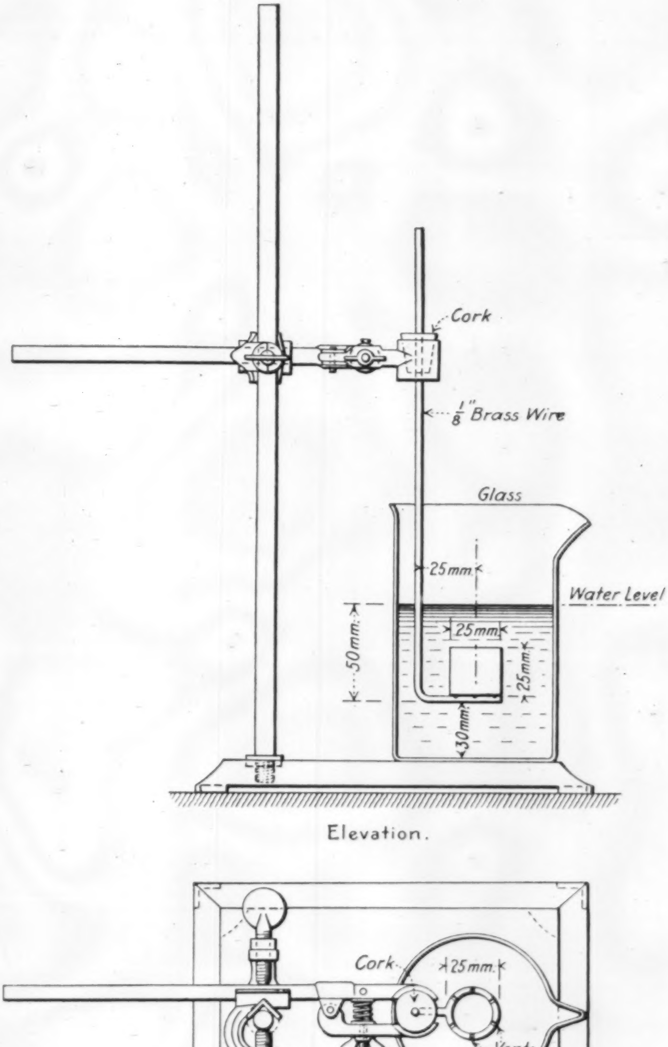
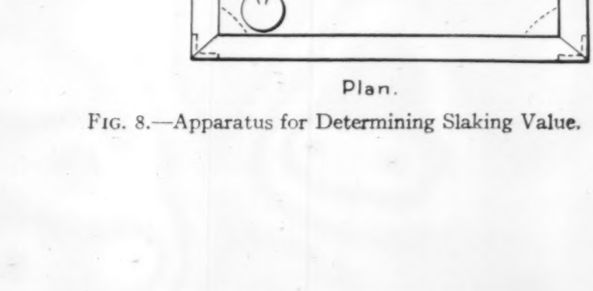


FIG. 7.—Apparatus for Determining the Dye-Adsorption of Soils.

Adsorption Test.—This test in its present form has been developed by E. C. E. Lord, of the Bureau of Public Roads, to determine the


Cork
1/8" Brass Wire
Glass
25mm.
Water Level
25mm.
50mm.
25mm.
30mm.

Elevation.


Cork
25mm.
Vents

Plan.

FIG. 8.—Apparatus for Determining Slaking Value.

adsorption of basic analine dye by soils. It probably is an indication of the binding property and bearing value of subgrade materials, and is carried out on air-dried material passing the 10-mesh sieve and on the silt, clay and suspension clay obtained as previously described from the 25-g. sample of soil.

The dye solution employed in this test consists of one part per thousand crystal violet in distilled water and a sufficient quantity should be made up in advance to assure a constant strength for a large number of tests.

The test is carried out as follows: A sample of the soil weighing 0.20 g. is transferred by means of a wide-necked funnel to a cylindrical separatory tube of about 5-cc. capacity containing about 1 cc. of the solution and is then thoroughly stirred with a platinum or polished brass rod until the solution is completely decolorized and the coagulated clay sinks to the bottom of the tube. It is then run into a filtering tube inserted in an upright position in a 25-cc. graduate, as shown in Fig. 7. This filter tube should measure about 6 by $\frac{1}{2}$ in. inside diameter and be drawn at the lower end for a distance of 1 in. to a straight stem having a $\frac{1}{8}$-in. inside diameter. The tube is closed by a small disk of filter paper firmly held in place by a ground glass stopper tube which encloses the end of the stem for a distance of $\frac{1}{4}$ in. as indicated in the diagram. It should be filled with water to assure an even flow of liquid through the soil to be tested and the filter paper should be pressed in place when wet.

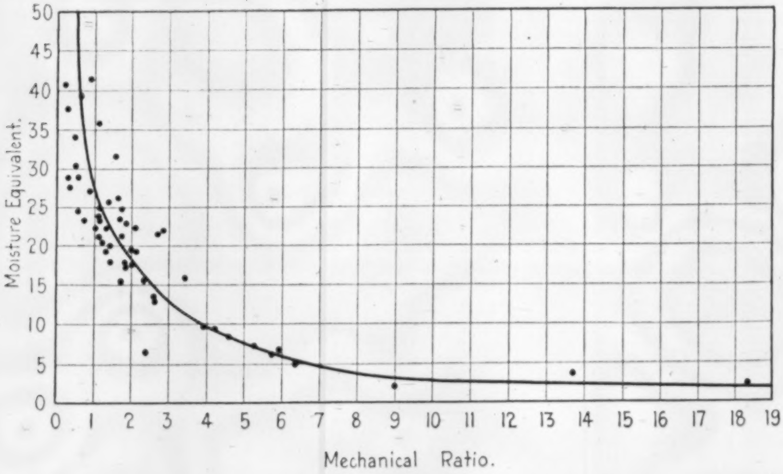


FIG. 9.—Relation between Mechanical Ratio and Moisture Equivalent.

The filter tube containing the flocculated soil and decolorized liquid is allowed to drain off into the graduate, when additional dye is added and the filtration continued until a marked coloration appears in the liquid passing the filter paper, indicating the end point of the reaction. The volume of decolorized solution is then read off in cubic centimeters as shown in the diagram.

The tests for silt, clay and suspension clay, as obtained by the mechanical analysis of the sample, are carried out in the same manner excepting when the quantity of material obtained is very small, requiring a more dilute dye solution (1 : 5000), or when the original soil consists mainly of silt and sand. In the latter case, the weighed sample is washed directly into the filtration tube and the water allowed to drain off before adding the dye.

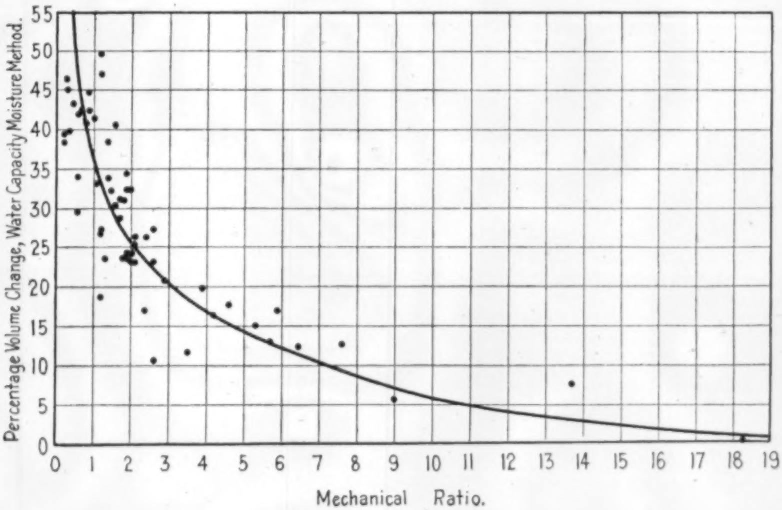


FIG. 10.—Relation between Mechanical Ratio and Percentage Volume Change, Water Capacity Moisture Method.

The results of the tests are recorded in cubic centimeters of dye at a concentration of 1 : 1000 adsorbed for unit values (1 g.) of the silt, clay, suspension clay, and soil as a whole.

Slaking Value.—This test in its present form can only be considered as tentative as it is felt that it can be considerably improved upon. It will be given, however, in order that we may benefit by any suggestions which might be offered.

A quantity of soil approximately 400 g. in weight is mixed with water until it has a consistency comparable with the "normal consistency" of portland cement. It is then pressed firmly into the mold by hand until filled, the surface being troweled off smooth. After remaining in the mold for about three hours, the briquettes are removed and are allowed to air dry for approximately eighteen hours, after which time they are placed in an oven (temperature not to exceed 100° C.) and dried for five hours. At the expiration of this time, the briquettes are placed in a desiccator until cool and then tested by means of the apparatus shown in Fig. 8. The slaking value is the time in minutes required for the briquette to fall through the brass ring. The slaking value given in the table is the average of the three most consistent values obtained from the four briquettes tested.

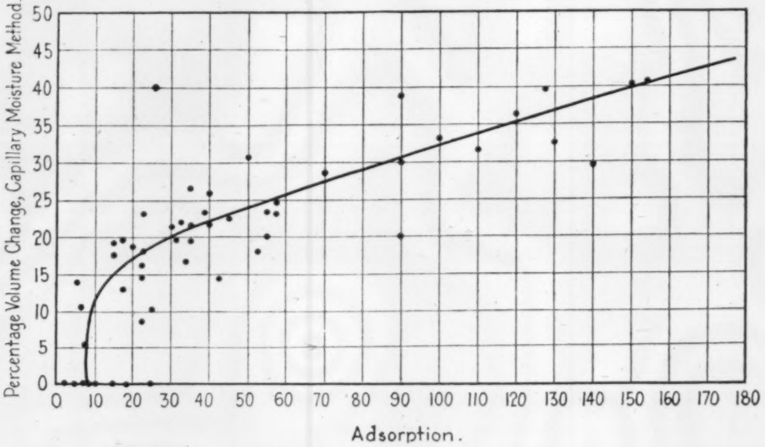


FIG. 11.—Relation between Adsorption and Percentage Volume Change, Capillary Moisture Method.

DEFINITION OF TERMS.

Owing to the many different interpretations placed upon such terms as sand, silt, clay, and suspension clay it is deemed advisable, in order to avoid confusion, to define these terms according to the sense in which they are used at the U. S. Bureau of Public Roads.

Sand.—That portion of the soil sample which passes a 10-mesh sieve and which is retained on a 200-mesh sieve and which settles out of a mixture of soil and water after eight minutes' subsidence to a depth of 8 cm. from the surface of the liquid.

Silt.—That portion of the soil sample which *passes* a 200-mesh sieve and which settles out of a mixture of soil and water after eight minutes' subsidence to a depth of 8 cm. from the surface of the liquid.

Clay.—That portion of the soil sample which remains in suspension after eight minutes' subsidence to a depth of 8 cm. from the surface of the liquid, but which is thrown down when a centrifugal force equal to 500 times the force of gravity is exerted upon the suspended material for a period of one-half hour.

Suspension Clay.—That portion of the soil sample which remains in suspension when a centrifugal force equal to approximately 500 times the force of gravity is exerted upon the suspended material for a period of one-half hour. The suspended material is obtained as described under "Mechanical Analysis."

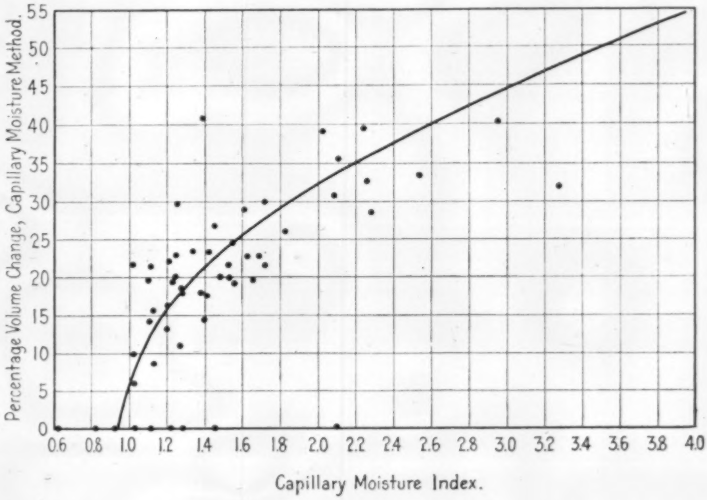


FIG. 12.—Relation between Capillary Moisture Index and Percentage Volume Change, Capillary Moisture Method.

Mechanical Ratio.—The mechanical ratio of a soil is the quotient obtained by dividing the sum of the percentage of sand and the percentage of silt by the sum of the percentage of clay and the percentage of suspension clay, the percentages used being those obtained from the mechanical analysis. This ratio expresses the relation between the inert material (sand and silt) and the active material (clay and suspension clay).

Percentage of Voids.—The percentage of voids of a soil can be expressed by the following formula:

$$\text{Percentage of voids} = \frac{\text{Apparent volume of soil} - \text{true volume of soil}}{\text{Apparent volume of soil}} \times 100$$

The data necessary to compute the apparent and true volume of the soil are obtained from the volumetric test of the soil under water-capacity conditions. A sample calculation for determining this factor is given below:

Weight of mercury required to fill dish alone........... = 175.09 g.
Weight of mercury required to fill dish after soil has dried to constant weight.............................. = 46.62 g.
Weight of mercury required to displace dried soil....... = 128.47 g.
Apparent volume of soil = $\frac{128.47}{13.6 \text{ (sp. gr. Hg.)}}$........... = 9.45 cc.
Weight of dried soil.............................. = 16.89 g.
True volume of dried soil = $\frac{16.89}{2.62 \text{ (sp. gr. of soil)}}$....... = 6.45 cc.
Cubic centimeters of voids in dried soil = 9.45 − 6.45... = 3.00
Percentage of voids in dried soil = $\frac{3.00}{9.45} \times 100$......... = 31.8

Moisture Index.—This factor is the ratio between the volume of moisture in the soil and the volume of voids in the soil when it has dried from its water-capacity condition. This may be expressed in algebraic form as follows:

$$\text{Moisture Index} = \frac{\text{Volume of moisture}}{\text{Apparent volume of soil} - \text{solid content of soil}}$$

The moisture equivalent index and the capillary moisture index are obtained by substituting the moisture-equivalent moisture and the capillary moisture, respectively, in the above formula.

Both of the above indices are calculated on the basis of 100 g. of soil, that is, the numerator is the weight of moisture in 100 g. of soil and the denominator is the volume of voids in 100 g. of soil.

DISCUSSION OF RESULTS.

The curves which have been plotted from the data given in Table I are not for the purpose of showing any mathematical relations which may exist between the various physical properties of subgrade soils, but are more for showing those general relations which have been found to exist.

TABLE I.—SHOWING RESULTS OF TESTS OBTAINED FROM COMPLETE AN

Soil No.	Mechanical Analysis.									Adsorption Numbers.				Percentage Moisture Obtained by		
	Total Sand.	Sand, per cent between Sieves.				Fine Material.				Dye Adsorbed by 1 g. of Material, cc.				Moisture Equivalent Test.	Vertical Capillarity Test.	Water Capacity Test.
		10–20	20–50	50–100	100–200	Total.	Silt.	Clay.	Suspension Clay.	Soil.	Silt.	Clay.	Suspension Clay			
1	69.2	17.6	40.8	7.2	3.6	30.8	3.2	26.8	0.8	10.0	1.3	26.6	182.8	12.8	15.0	22.2
3	38.8	1.6	7.2	15.6	14.4	61.2	26.4	33.2	1.6	15.0	2.5	30.2	89.3	17.6	28.4	38.2
4	52.0	7.2	20.0	11.2	13.6	48.0	20.4	25.6	2.0	35.0	7.5	118.0	111.1	13.5	28.2	34.9
5	70.4	6.8	34.4	15.2	14.0	29.6	18.0	10.8	0.8	7.5	6.3	53.5	181.8	7.2	20.4	25.3
6	41.2	7.6	15.6	8.4	9.6	58.8	26.8	30.0	2.0	22.5	6.3	52.8	141.8	22.8	32.1	44.1
7	12.8	3.2	4.0	2.4	3.2	87.2	22.8	62.8	1.6	40.0	6.3	56.9	125.5	30.3	37.7	50.3
8	2.8	0.0	0.8	0.4	1.6	97.2	50.8	43.2	3.2	30.0	3.8	56.4	129.1	23.8	30.3	45.9
9	4.4	0.4	1.6	1.2	1.2	95.6	51.6	41.6	2.4	22.5	2.5	44.5	73.5	20.4	28.6	36.9
10	15.6	0.8	3.2	4.4	7.2	84.4	58.6	23.6	2.2	22.5	3.7	77.1	63.2	22.0	30.8	43.6
11	31.2	0.4	9.2	11.6	10.0	68.8	46.4	21.2	1.2	8.3	2.5	26.8	66.6	15.8	22.2	29.0
12	37.6	2.8	16.4	11.2	7.2	62.4	25.6	33.2	3.6	17.5	5.0	38.8	66.5	15.4	26.6	44.3
13	12.0	2.0	4.0	2.0	4.0	88.0	42.0	44.8	1.2	17.5	5.0	28.5	60.2	23.3	33.1	42.1
14	26.8	2.8	7.2	7.2	9.6	73.2	24.4	46.0	2.8	55.0	8.8	111.8	138.9	22.2	27.3	47.6
15	26.4	5.2	6.0	5.2	10.0	73.6	32.0	38.8	2.8	22.5	10.0	40.6	128.5	25.6	31.8	49.2
16	34.0	3.6	7.2	4.8	18.4	66.0	27.2	36.4	2.4	80.0	5.0	175.8	128.2	31.7	34.5	62.4
17	22.4	3.2	4.8	5.2	9.2	77.6	25.6	48.4	3.6	70.0	5.0	115.2	108.7	26.8	28.8	51.2
19	28.4	2.0	5.2	6.0	15.2	71.6	42.0	26.0	3.6	15.0	2.5	21.8	125.0	15.6	27.7	36.7
20	9.2	0.8	2.0	2.0	4.4	90.8	15.6	72.0	3.2	130.0	2.5	182.7	92.6	28.8	30.6	56.1
22	18.0	2.0	6.0	4.0	6.0	82.0	25.2	53.6	3.2	90.0	7.5	148.9	166.6	23.4	25.1	46.6
23	47.2	5.2	16.4	12.8	12.8	52.8	12.0	37.6	3.2	57.5	6.3	113.6	107.1	17.7	27.8	51.5
24	22.4	0.8	2.4	8.8	10.4	77.6	24.8	49.2	3.6	90.0	10.0	142.8	83.3	27.0	41.1	61.7
25	28.4	4.0	8.0	8.8	7.6	71.6	25.9	41.6	4.1	150.0	12.5	371.0	216.0	35.8	47.0	67.8
26	15.2	2.0	3.6	4.0	5.6	84.8	24.4	56.0	4.4	154.8	7.5	256.0	160.7	39.5	43.1	67.2
27	20.8	2.8	6.0	4.8	7.2	79.2	27.2	48.8	3.2	127.5	7.5	261.1	111.8	41.4	57.3	69.2
28	22.0	0.4	6.0	5.6	10.0	78.0	44.0	30.4	3.6	45.0	6.3	37.7	57.5	19.2	42.4	45.4
29	66.0	0.4	30.8	22.4	12.4	34.0	4.7	26.3	3.0	25.0	6.3	86.9	93.9	6.3	17.7	29.9
30	84.0	7.2	43.6	22.4	10.8	16.0	6.0	8.8	1.2	5.0	1.3	32.3	54.3	2.0	18.8	22.7
31	13.2	0.4	1.2	2.8	8.8	86.8	23.2	60.4	3.2	100.0	7.5	241.0	58.1	24.6	33.1	47.1
32	53.6	3.2	20.4	17.6	12.4	46.4	13.2	31.6	1.6	42.5	7.5	77.3	90.9	17.4	23.0	34.8
33	3.6	0.4	1.2	0.8	1.2	96.4	29.5	64.2	2.7	90.0	22.5	129.4	159.4	34.0	35.2	61.6
34	45.6	2.0	7.6	16.0	20.0	54.4	21.2	30.8	2.4	33.8	8.8	51.1	75.8	19.4	24.8	36.6
36	41.6	2.4	8.8	13.6	16.8	58.4	22.0	34.4	2.0	31.3	12.5	75.0	125.0	20.2	34.3	39.3
37	23.2	2.0	11.2	6.8	3.2	76.8	39.2	34.4	3.2	55.0	17.5	66.2	64.8	26.1	35.2	55.4
38	90.4	1.6	20.4	44.4	24.0	9.6	2.8	5.6	1.2	7.5	2.5	77.3	55.6	3.5	22.2	24.6
42	8.4	0.4	0.8	1.2	6.0	91.6	9.6	70.8	11.2	120.0	2.5	141.0	113.0	40.7	46.8	49.8
44	18.0	4.0	6.4	2.4	5.2	82.0	10.4	68.4	3.2	140.0	7.5	229.3	190.5	27.6	30.6	63.0
50	17.6	1.2	4.8	4.8	6.8	82.4	43.6	36.0	2.8	38.8	20.0	82.0	97.1	23.4	35.7	54.9
51	38.0	3.2	12.8	11.2	10.8	62.0	19.0	39.6	3.4	52.5	7.5	114.9	62.5	22.2	27.4	50.1
55	14.4	1.6	6.0	3.6	3.2	85.6	49.6	33.6	2.4	55.0	7.5	148.0	121.0	24.7	26.6	47.2
56	6.0	0.8	2.4	1.2	1.6	94.0	66.0	24.0	4.0	18.8	11.3	53.0	44.6	21.4	33.3	47.2
59	8.8	0.0	3.2	4.0	1.6	91.2	56.4	31.6	3.2	40.0	8.8	95.9	65.8	22.9	29.9	54.8
80	31.6	2.8	8.0	7.6	13.2	68.4	26.6	39.2	2.6	22.5	3.8	43.9	81.1	19.2	25.8	40.9
92	55.2	1.6	14.4	18.8	20.4	44.8	12.8	30.0	2.0	35.0	5.0	38.6	214.3	19.2	31.3	42.0
119	14.4	0.8	2.8	4.0	6.8	85.6	40.0	43.6	2.0	20.0	5.0	23.0	154.0	21.1	32.5	43.1
120	1.6	0.0	0.4	0.4	0.8	98.4	22.0	73.6	2.8	50.0	22.5	82.5	93.4	37.3	40.9	65.8
157	35.6	2.4	7.2	10.0	16.0	64.4	18.8	41.2	4.4	110.0	7.5	103.7	99.0	24.8	31.3	57.5
158	94.0	9.2	45.6	28.0	11.2	6.0	0.8	4.0	1.2	2.5	5.0	35.7	80.6	2.2	17.4	23.3
186	43.6	2.4	7.6	12.8	20.8	56.4	21.4	31.6	3.4	35.0	7.5	90.4	103.0	17.3	30.6	41.7
188	78.4	22.4	30.8	14.8	10.4	21.6	6.7	13.4	1.5	15.0	2.5	85.1	90.9	6.1	18.7	26.1
200	26.8	1.6	4.4	4.8	16.0	73.2	32.8	36.4	4.0	57.5	5.0	140.6	107.1	20.0	31.0	46.9
201	70.8	15.2	28.8	15.2	11.6	29.2	8.8	18.8	1.6	15.0	3.8	61.0	101.6	9.6	23.6	32.7
202	70.0	8.8	27.6	18.8	14.8	30.0	12.0	16.0	2.0	25.0	5.0	115.6	130.7	8.2	13.8	30.3
290	74.4	8.0	29.6	22.8	14.0	25.6	9.6	14.4	1.6	6.3	2.5	30.0	91.0	6.8	19.3	29.0
291	65.6	6.8	23.2	20.0	15.6	34.4	15.2	17.6	1.6	7.5	2.5	40.2	136.5	9.4	21.0	30.9
292	30.0	1.3	9.4	11.6	7.7	70.0	6.9	61.0	2.1	32.5	10.0	50.4	89.2	28.9	51.4	70.2
293	74.8	9.6	30.8	21.6	12.8	25.2	10.8	12.0	2.4	7.5	2.5	36.0	69.4	6.6	18.7	30.0
294	77.6	4.0	30.0	27.2	16.4	22.4	8.8	12.0	1 6	7.5	5.0	36.1	160.0	4.9	19.0	25.7

Plate I.
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Boyd on Properties of Subgrade
Materials.

te Analysis of Fifty-Seven Different Subgrade Soils.

d by	Percentage Volume Change Obtained when Soil is Mixed with			Bearing Value, lb. per sq. in. when Soil is Mixed with		Slaking Value.	Specific Gravity.	Mechanical Ratio.	Voids, per cent.	Moisture Equivalent Index.	Capillary Moisture Index.	Adsorption Number of Soil × Capillary Moisture Index.	Soil No.
ater pacity 'est.	Moisture Equivalent Moisture.	Vertical Capillarity Moisture.	Water Capacity Moisture.	Moisture Equivalent Moisture.	Vertical Capillarity Moisture.								
22.2	0.0	0.0	10.6	16.5	5.0	1	2.62	2.63	29.8	0.79	0.93	9.3	1
38.2	6.4	17.6	23.6	18.9	0.0	20	2.68	1.87	35.3	0.87	1.41	21.2	3
34.9	5.1	21.6	27.2	20.+	0.0	3	2.64	2.62	32.9	0.73	1.52	53.2	4
25.3	0.0	10.7	12.6	20.+	0.0	1–	2.71	7.63	31.4	0.43	1.21	9.1	5
24.1	6.5	16.2	25.4	20.+	1.2	16	2.66	2.12	41.5	0.86	1.20	27.0	6
50.3	22.0	26.0	34.2	6.4	1.8	39	2.72	0.55	36.3	1.47	1.83	73.2	7
45.9	13.9	21.5	27.2	3.3	1.7	21	2.69	1.16	42.5	0.87	1.11	33.3	8
36.9	0.0	14.6	23.6	17.4	1.8	15	2.67	1.27	35.1	1.01	1.41	31.7	9
43.6	0.0	8.5	20.6	20.+	1.7	4	2.67	2.88	41.9	0.82	1.14	25.7	10
29.0	0.0	0.0	11.5	20.+	2.0	2	2.66	3.47	36.5	0.73	1.03	8.5	11
44.3	6.6	19.7	27.7	20.+	1.7	39	2.67	1.72	36.5	0.72	1.23	21.5	12
42.1	5.9	13.0	18.8	20.+	2.0	5	2.68	1.18	42.7	0.84	1.20	21.0	13
47.6	18.0	23.4	33.1	15.7	3.3	300+	2.58	1.05	33.1	1.15	1.42	78.2	14
49.2	18.9	23.2	38.4	2.9	1.3	36	2.64	1.40	34.1	1.31	1.63	36.7	15
62.4	28.0	29.0	40.6	4.5	2.9	59	2.55	1.58	35.1	1.48	1.61	128.8	16
51.2	28.0	28.6	41.4	8.9	6.6	65	2.50	0.92	24.0	2.12	2.28	159.6	17
36.7	7.6	19.2	26.4	13.4	1.1	6	2.62	2.37	31.8	0.88	1.56	23.4	19
56.1	31.6	32.5	45.1	13.9	6.9	5	2.56	0.33	26.5	2.12	2.26	294.0	20
46.6	28.6	30.0	40.7	19.5	11.7	6	2.62	0.76	27.6	1.61	1.72	154.9	22
51.5	12.4	23.1	32.2	20.+	13.5	7	2.54	1.45	35.9	0.79	1.26	72.4	23
61.7	29.2	39.0	44.8	20.+	2.3	2	2.63	0.90	34.7	1.34	2.03	182.7	24
67.8	36.6	40.2	47.0	9.9	0.9	2	2.42	1.19	29.2	2.10	2.76	414.0	25
67.2	40.9	40.7	42.3	3.9	3.5	2	2.53	0.66	43.9	1.27	1.39	215.2	26
69.2	36.2	39.7	42.4	3.1	0.0	1	2.55	0.92	39.6	1.61	2.24	285.2	27
45.4	5.6	22.6	24.0	14.9	0.0	7	2.70	1.94	40.4	0.76	1.69	76.1	28
29.9	0.0	10.0	17.2	20.+	2.2	4	2.70	2.41	31.9	0.36	1.02	25.5	29
22.7	0.0	0.0	6.0	20.+	0.0	. .	2.69	9.00	31.1	0.12	1.12	5.6	30
47.1	26.9	33.2	41.8	20.+	2.9	4	2.66	0.58	27.4	1.74	2.34	234.0	31
34.8	8.4	14.4	23.0	14.2	1.7	8	2.67	2.01	31.4	1.01	1.34	56.9	32
61.6	20.0	20.0	43.2	7.9	7.3	18	2.65	0.50	37.8	1.48	1.53	137.7	33
36.6	7.1	16.7	24.4	20.+	4.5	. .	2.63	2.01	36.6	0.88	1.13	38.2	34
39.3	6.7	19.7	23.6	20.+	1.0	11	2.57	1.76	34.7	0.98	1.66	52.0	36
55.4	11.3	20.0	31.0	20.+	16.0	300+	2.43	1.66	38.0	1.03	1.39	76.4	37
24.6	0.0	0.0	7.8	20.+	6.4	1–	2.64	13.70	35.5	0.17	1.06	8.0	38
49.8	36.2	36.5	38.4	20.+	20.+	5	2.73	0.22	37.8	1.83	2.11	253.2	42
63.0	26.4	29.6	39.6	20.+	14.3	5	2.65	0.39	39.1	1.14	1.26	176.5	44
54.9	14.6	23.4	30.2	20.+	1.6	300+	2.58	1.57	40.7	0.88	1.34	52.0	50
50.1	16.4	18.0	32.2	8.4	2.3	6	2.69	1.32	36.5	1.04	1.29	67.8	51
47.2	17.4	20.0	31.4	5.6	2.6	21	2.63	1.77	36.1	1.15	1.24	68.2	55
47.2	0.0	0.0	23.0	20.+	0.9	2	2.61	2.57	43.9	0.71	1.11	20.9	56
54.8	17.5	21.6	34.6	10.0	2.1	8	2.67	1.87	38.3	0.99	1.29	51.6	59
40.9	12.2	18.0	33.8	7.3	1.4	42	2.72	1.39	33.7	1.03	1.38	31.0	80
42.0	5.8	19.5	26.3	20.+	1.1	4	2.61	2.13	42.7	0.67	1.10	38.5	92
43.1	5.2	18.8	27.0	18.2	0.8	5	2.65	1.19	39.9	0.84	1.30	26.0	119
65.8	28.0	30.9	46.4	20.+	14.1	10	2.73	0.31	34.7	1.91	2.09	104.5	120
57.5	27.4	31.8	49.6	20.+	15.7	6	2.65	1.19	21.2	2.44	3.08	338.8	157
23.3	0.0	0.0	0.0	20.+	20.+	1–	2.73	18.30	43.6	0.08	0.62	1.6	158
41.7	6.0	26.7	32.3	20.+	0.0	24	2.64	1.85	35.9	0.82	1.45	50.8	186
26.1	0.0	0.0	13.0	20.+	1.2	1	2.63	5.71	28.7	0.40	1.22	18.2	188
46.9	11.7	24.6	30.3	16.5	1.7	17	2.70	1.47	35.1	1.00	1.55	89.2	200
32.7	0.0	0.0	19.8	20.+	1.0	11	2.70	3.91	33.0	0.53	1.29	19.4	201
30.3	0.0	0.0	17.7	20.+	9.2	3	2.63	4.56	30.8	0.47	0.82	20.5	202
29.0	0.0	14.0	15.0	20.+	0.2	17	2.64	5.25	31.4	0.39	1.11	7.0	290
30.9	0.0	6.0	16.4	20.+	3.5	33	2.61	4.21	34.9	0.46	1.02	7.7	291
70.2	8.8	22.0	29.4	20.+	20.+	43	2.64	0.59	52.7	0.68	1.21	39.4	292
30.0	0.0	0.0	17.0	20.+	1.9	6	2.63	5.94	30.4	0.39	1.11	8.3	293
25.7	0.0	0.0	12.2	20.+	3.6	8	2.65	6.35	33.1	0.26	1.02	7.7	294

In Fig. 9 the moisture equivalent of the soil has been plotted against its mechanical ratio, showing that as the mechanical ratio decreases, the moisture equivalent increases. This means that as the clay content of a soil increases, the percentage of moisture which can be retained in the soil by a force equal to 1000 times the force of gravity increases. This relation should prove useful in studying the problem of subgrade drainage as it is reasonable to suppose that soils having low moisture equivalents can be more easily drained than those having high moisture equivalents.

In Fig. 10 the percentage volume change under water-capacity conditions has been plotted against the mechanical ratio, showing that as the mechanical ratio decreases the percentage volume change increases.

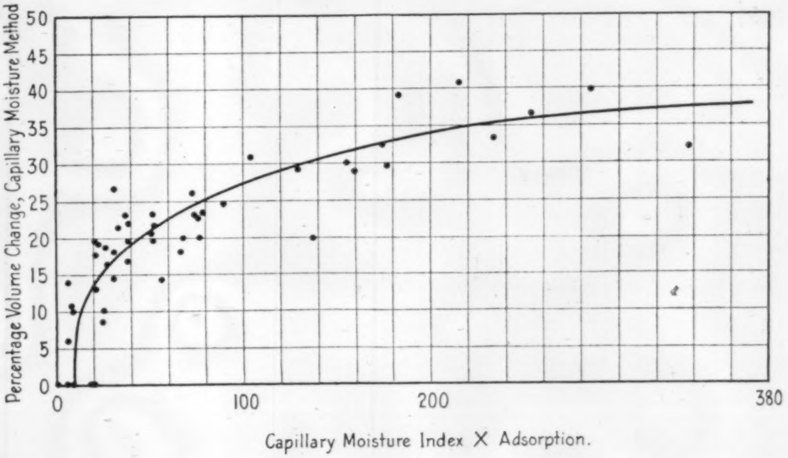

FIG. 13.—Relation between Capillary Moisture Index × Adsorption and Percentage Volume Change, Capillary Moisture Method.

It has also been shown that a relation exists between the percentage volume change of a soil and its adsorption number and between the percentage volume change and the capillary moisture index. These relations are shown in Figs. 11 and 12, respectively.

In considering the volume change of a soil, we find from the above relations that it is dependent upon the quantity and character of the clay content of the soil as well as upon the moisture content of the soil, consequently Fig. 13 is an attempt to express these relations by one curve in which the percentage volume change has been plotted against the product obtained by multiplying the capillary moisture index of the soil by its adsorption and we find that as this product increases in value, the percentage volume change also increases.

Attempts have been made to plot curves involving bearing values and the other physical characteristics of a soil, but no definite relations have been obtained. This is undoubtedly due to the large number of variables involved.

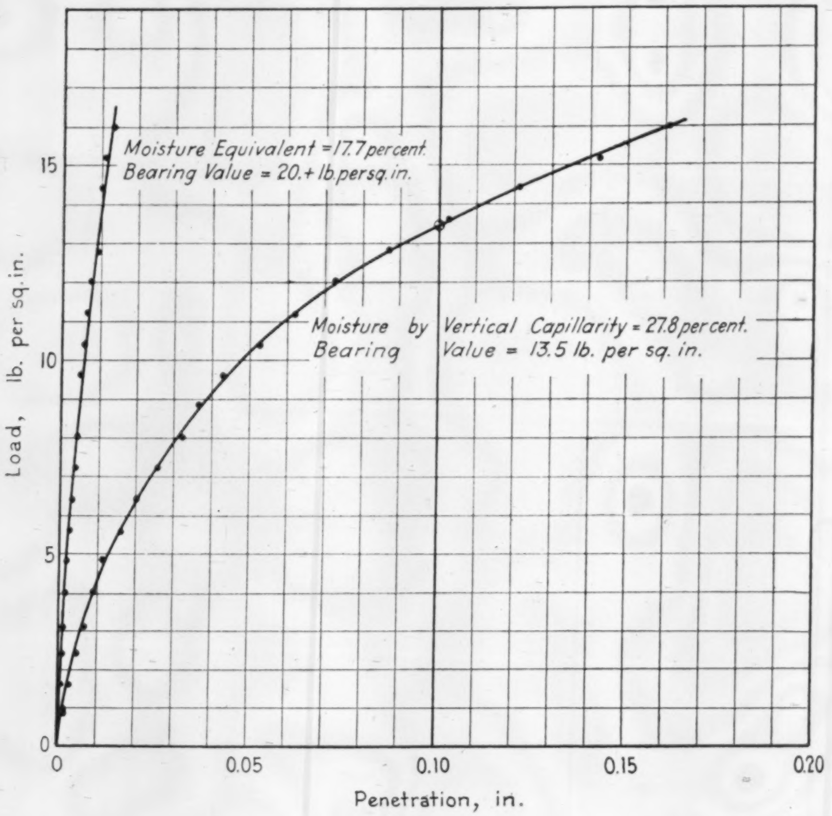

Fig. 14.—Relation between Load and Penetration. Soil No. 23.

In Table II the soils have been classified according to high and low bearing values under capillary moisture conditions, respectively. It is impossible to draw a sharp line between these two classes, but in order to make comparisons, 5 lb. per sq. in. has been taken as the dividing line. Some interesting facts are to be noted from an examination of Table II. Soils which are rich in clay, that is, those having mechanical ratios less than unity, have high bearing values, *provided* the adsorption of the soil is high, and also in general have high capillary moisture indices. This would indicate that those soils which are rich in clay and also highly adsorptive have the ability to take up considerably more water than those which are rich in clay and not highly adsorptive and still maintain good bearing value. It is also interesting to note that a combination of high clay content, high adsorption and high bearing value is accompanied by high volume change. It would seem that soils of this nature could be greatly improved upon by the addition of some material, such as sand, which would tend to reduce the volume change of the soil. It seems reasonable to suppose that when the cubic centimeters of moisture in the soil is less than the cubic centimeters of voids which exist in the dry soil, the soil should give good

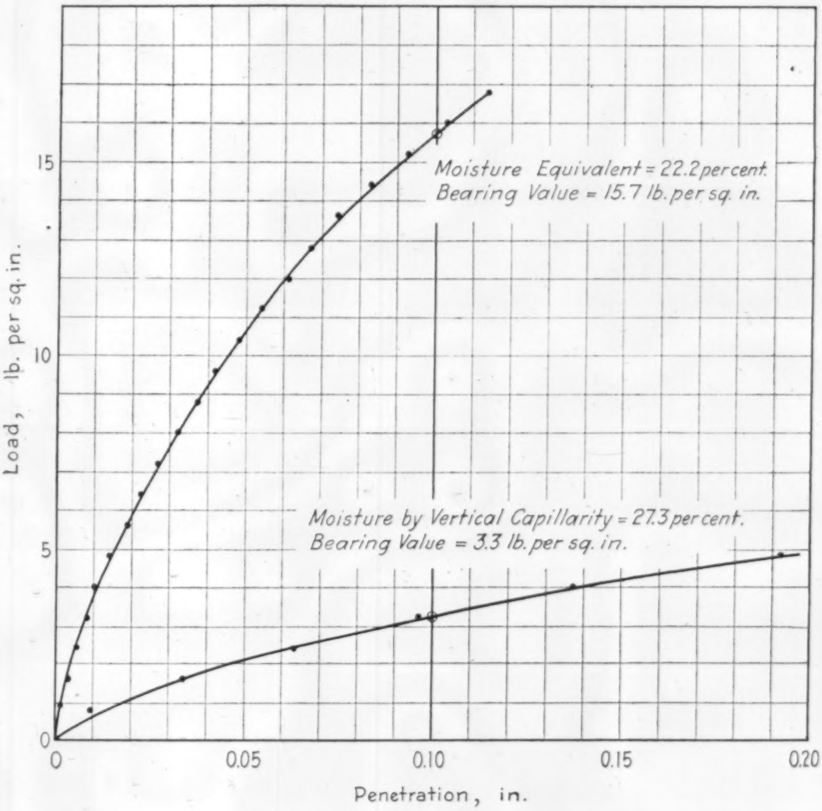

FIG. 15.—Relation between Load and Penetration. Soil No. 14.

TABLE II.—PROPERTIES OF SOILS.

Soil No	Mechanical Ratio.	Adsorption of Soil.	Percentage Volume Change when mixed with		Bearing Value, lb. per sq. in., when mixed with		Moisture Equivalent Index.	Capillary Moisture Index.
			Moisture-Equivalent Moisture.	Vertical-Capillarity Moisture.	Moisture-Equivalent Moisture.	Vertical-Capillarity Moisture.		
HIGH BEARING VALUE.								
1	2.63	10.0	0.0	0.0	16.5	5.0	0.79	0.93
17	0.92	70.0	28.0	28.6	8.9	6.6	2.12	2.28
20	0.33	130.0	31.6	32.5	13.9	6.9	2.12	2.26
22	0.76	90.0	28.6	30.0	19.5	11.7	1.61	1.72
23	1.45	57.5	12.4	23.1	20.+	13.5	0.79	1.26
33	0.50	90.0	20.0	20.0	7.9	7.3	1.48	1.53
37	1.66	55.0	11.3	20.0	20.+	16.0	1.03	1.39
38	13.70	7.5	0.0	0.0	20.+	6.4	0.17	1.06
42	0.22	120.0	36.2	36.5	20.+	20.+	1.83	2.11
44	0.39	140.0	26.4	29.6	20.+	14.3	1.14	1.26
120	0.31	50.0	28.0	30.9	20.+	14.1	1.91	2.09
157	1.19	110.0	27.4	31.8	20.+	15.7	2.44	3.08
158	18.30	2.5	0.0	0.0	20.+	20.+	0.08	0.62
202	4.56	25.0	0.0	0.0	20.+	9.2	0.47	0.82
292	0.59	32.5	8.8	22.0	20.+	20.+	0.68	1.21
LOW BEARING VALUE.								
3	1.87	15.0	6.4	17.6	18.9	0.0	0.87	1.41
4	2.62	35.0	5.1	21.6	20.+	0.0	0.73	1.52
5	7.63	7.5	0.0	10.7	20.+	0.0	0.43	1.21
6	2.12	22.5	6.5	16.2	20.+	1.2	0.86	1.20
7	0.55	40.0	22.0	26.0	6.4	1.8	1.47	1.83
8	1.16	30.0	13.9	21.5	3.3	1.7	0.87	1.11
9	1.27	22.5	0.0	14.6	17.4	1.8	1.01	1.41
10	2.88	22.5	0.0	8.5	20.+	1.7	0.82	1.14
11	3.47	8.3	0.0	0.0	20.+	2.0	0.73	1.03
12	1.72	17.5	6.6	19.7	20.+	1.7	0.72	1.23
13	1.18	17.5	5.9	13.0	20.+	2.0	0.84	1.20
14	1.05	55.0	18.0	23.4	15.7	3.3	1.15	1.42
15	1.40	22.5	18.9	23.2	2.9	1.3	1.31	1.63
16	1.58	80.0	28.0	29.0	4.5	2.9	1.48	1.61
19	2.37	15.0	7.6	19.2	13.4	1.1	0.88	1.56
24	0.90	90.0	29.2	39.0	20.+	2.3	1.34	2.03
25	1.19	150.0	36.6	40.2	9.9	0.9	2.10	2.76
26	0.66	154.8	40.9	40.7	3.9	3.5	1.27	1.39
27	0.92	127.5	36.2	39.7	3.1	0.0	1.61	2.24
28	1.94	45.0	5.6	22.6	14.9	0.0	0.76	1.69
29	2.41	25.0	0.0	10.0	20.+	2.2	0.36	1.02
30	9.00	5.0	0.0	0.0	20.+	0.0	0.12	1.12
31	0.58	100.0	26.9	33.2	20.+	2.9	1.74	2.34
32	2.01	42.5	8.4	14.4	14.2	1.7	1.01	1.34
34	2.01	33.8	7.1	16.7	20.+	4.5	0.88	1.13
36	1.76	31.3	6.7	19.7	20.+	1.0	0.98	1.66
50	1.57	38.8	14.6	23.4	20.+	1.6	0.88	1.34
51	1.32	52.5	16.4	18.0	8.4	2.3	1.04	1.29
55	1.77	55.0	17.4	20.0	5.6	2.6	1.15	1.24
56	2.57	18.8	0.0	0.0	20.+	0.9	0.71	1.11
59	1.87	40.0	17.5	21.6	10.0	2.1	0.99	1.29
80	1.39	22.5	12.2	18.0	7.3	1.4	1.03	1.38
92	2.13	35.0	5.8	19.5	20.+	1.1	0.67	1.10
119	1.19	20.0	5.2	18.8	18.2	0.8	0.84	1.30
186	1.85	35.0	6.0	26.7	20.+	0.0	0.82	1.45
188	5.71	15.0	0.0	0.0	20.+	1.2	0.40	1.22
200	1.47	57.5	11.7	24.6	16.5	1.7	1.00	1.55
201	3.91	15.0	0.0	0.0	20.+	1.0	0.53	1.29
290	5.25	6.3	0.0	14.0	20.+	0.2	0.39	1.11
291	4.21	7.5	0.0	6.0	20.+	3.5	0.46	1.02
293	5.94	7.5	0.0	0.0	20.+	1.9	0.39	1.11
294	6.35	7.5	0.0	0.0	20.+	3.6	0.26	1.02

bearing value. This condition is fulfilled when the moisture index of the soil is less than unity. Table II shows that with only one exception, the bearing value is high when the moisture index is less than unity. On the other hand, it is possible to obtain high bearing values when the moisture index is as high as 2.0, but it should be noted that in these cases the adsorption is generally high. It is evident that with the exception of those soils which are highly adsorptive, as the moisture index of the soil increases above unity, the bearing value or stability of the soil decreases and it is believed by the author that every soil has a fairly definite critical moisture index, that is, an index above which the bearing value is good, and below which it is poor. During the coming year it is proposed to obtain data which will establish this index as well as the laws which govern it.

CONCLUSIONS.

As can be seen from the data in Table I and the curves, there seem to be at least three important factors upon which the physical properties of subgrade soils are dependent, namely, the gradation which is expressed by the mechanical ratio, the moisture content which is expressed by the moisture index, and the character of the soil which is expressed by the adsorption number.

These factors influence the physical properties of subgrade soils in the following manner:

When the clay content of the soil is increased, its ability to take up and retain moisture is increased and its percentage volume change is increased.

The character of a soil influences its percentage volume change as is evidenced by the fact that for increasing adsorption numbers, the percentage volume change increases (**Fig.** 11).

When the moisture index of the soil is less than unity, the bearing value will be high.

When the moisture index of the soil is above unity, high bearing values can be obtained, provided the adsorption of the soil is high.

In conclusion, the author wishes to emphasize the fact that the above statements are based on laboratory tests alone and can only be considered as being comparative, no attempt having been made to correlate this data with field conditions, although this phase is to be considered during the next year.

DISCUSSION.

Mr. Abrams. MR. D. A. ABRAMS.—I wish to ask the following questions:

1. How were the samples of soil obtained in the field and what was the method of securing the small samples for more complete analysis in the laboratory?

2. What is the relation between the mechanical analysis of these soils and their bearing value? That, of course, involves the question of the actual size determination of the particles separated by the various types of apparatus shown.

3. How does the so-called suspension clay compare with what is ordinarily termed colloidal materials in clay?

4. Was any study made of the movement of water through various soils?

5. Did any of the soil samples tested give compositions which correspond to that of the materials which have been found successful in constructing the sand-clay or top-soil roads in the Southern states?

Mr. Boyd. MR. J. R. BOYD.—In sampling in the field, a sample of about a cubic foot is taken from the sub-grade or from the shoulder and a description of it is sent to the laboratory with the sample. The material is then broken to pass a ten-mesh sieve, and that which is above the ten-mesh sieve is not used. It is not very difficult to get a uniform sample from a large container of material which all passes a ten-mesh sieve. In making mechanical analyses, we have had no difficulty in checking tests made one day against tests made a week later on the same material.

I believe attempts have been made, although we do not feel now that we would learn anything by going into the microscopical size of the particles; in other words, we just grade the material into four different classes, the sand, silt, clay and suspension clay.

As to what relation exists between suspension clay and colloidal clay, we avoided the term "colloidal clay," avoided defining that because we do not know exactly what the relation is. Unquestionably, in a large percentage of soils, the material that remains in suspension will have the characteristics of colloidal clay. On the other hand, we will come to another soil where the separation, as far as size is concerned, is the same, and in the course of a week or a month a portion of that material will begin to come down, so we cannot call it colloidal material, but call it suspension clay, which is more or less according to size. **Mr. Boyd.**

As to the last question, in Table II, I believe I am correct in saying that the last five soils are samples of soils taken from North Carolina and submitted to us for that very purpose. Now you will note at the same time that they are in the table classified as having low bearing values, but we analysed only the part of the material that passes the ten-mesh sieve and in all sand-clay roads of that nature, there is a larger aggregate of considerable value which we cannot analyse, but unquestionably if the large aggregate were considered, the other properties shown here would give a high supporting value to that type of soil.

Mr. Pearson. MR. J. C. PEARSON.—I would like to ask whether the single centrifuging operation would not give a rather incomplete separation of the very fine material, or similarly, whether the sedimentation test would not give a rather incomplete separation of the ordinary clay? In other words, would not the operation have to be repeated several times in order to get the full quantity?

Mr. Boyd. MR. BOYD.—No, it would not. We brought the volume of liquid up to ten liters before determining the suspension clay. We have found that if that material is washed carefully with a brush and allowed to settle 8 minutes, and this is repeated until the supernatant liquid is clear, we get a very good separation, but if the volume is not taken up to ten liters I believe the clay would take down portions from the lighter particles of suspension clay and you would not be able to get the best analysis of the soil. The best answer is that we are able to make check tests with mechanical analysis of these materials, and if we were not making proper separations, I do not believe we would be able to get similar results.

Mr. Pearson. MR. PEARSON.—I do not doubt that you would get check results, because it is a fairly definite percentage of the total you get each time, but if you have a uniform suspension when you start centrifuging, some of the material near the bottom goes out, whereas if it were farther up it would not have time to reach the bottom and would, therefore, remain in suspension. I know that in the ordinary decantation test you have to repeat a great many times to get a clean separation.

Mr. Boyd. MR. BOYD.—I think very likely that that is possible, but I do not believe we need a mechanical analysis for subgrade materials which would go that fine.

Mr. Fippin. MR. E. O. FIPPIN.—I would like to ask two or three questions, if I may: First, whether the measurement of the volume of pore space

Mr. Fippin. by the amount of the mercury that can be taken up was found accurate, or did you find a tendency of the soil to float and difficulty in actually holding it in place?

Mr. Boyd. MR. BOYD.—We did find that difficulty and overcame it by using a glass plate, which we pressed down over the soil pat in such a way that the pat was just held within the plane of the top of the container, so that the only mercury in the container is that which is not displaced by the soil. You might believe at the same time, that the soil being of a more or less porous nature, that the mercury would tend to go into the pores of the soil, but we have not found this to be the case. We get very nice pats, and by air-drying them, they seldom crack.

Mr. Fippin. MR. FIPPIN.—That would measure only the gross or pore space, because the high surface tension of the mercury would prevent it going in the fine pores. The next question is, whether you found any relation between the color or dye absorption of the soil and the percentage of suspension clay?

Mr. Boyd. MR. BOYD.—We have not attempted to. I do believe there would be a possible relation there.

Mr. Fippin. MR. FIPPIN.—The next question is, have you studied the penetration curve or bearing value of any particular soil through a range of moistures from very low to very high, and if so do you find that the curve is a smooth one, or does it break rather sharply at what might be called optimum moisture conditions with the tendency for the bearing value to go up very sharply when you reach the optimum moisture content?

Mr. Boyd. MR. BOYD.—We have been analyzing soils that have been submitted to the laboratory in an effort to determine relations between these materials where you have involved eight or nine variables; beginning practically from the present time, we are making mechanical mixtures in the laboratory, starting with 90 per cent of sand and 10 per cent of clay, and running this complete procedure upon these mixtures, except that whereas we have only been making two moisture tests for bearing value, we are now going to start with a minimum moisture content and increase it in 5-per-cent increments, until we get to the place where the soil has no supporting value, and from preliminary tests run six months ago, I am of the opinion that you can readily see beyond what moisture content the bearing value of the soil commences to become poor. I do not think you will find a curve that will run right up and break suddenly. I think you will be able, within narrow limits, to say what the critical moisture content of a soil is, that is, the point above which the bearing value is poor and below which it is good.

Mr. Fippin. MR. FIPPIN.—It seems to me that that is worthy of very careful study. One other question; I notice Mr. Boyd said they studied the volume changes of the soil from a puddled condition, which would mean that they would tend to have a maximum volume change. I would like to inquire whether you have taken account of that degree of granulation normally occurring in soils in the field and the effect this may have on the shrinkage of a soil.

Mr. Boyd. MR. BOYD.—The volumetric change is made under three moisture conditions; the maximum moisture condition was a condition in which the soil was almost puddled, the next is a rather dry mix, and then the condition in which the moisture corresponds to the equivalent condition, so the table represents three conditions of moisture, maximum, intermediate, and minimum, and I believe that the granular structure of the soil would enter into it when you use the moisture equivalent condition, which is very low in moisture.

Mr. Fippin. MR. FIPPIN.—I am intensely interested in this, because it touches a line of work to which I have given a good deal of study. I would suggest that a study be made of the possibility of draining, by artificial drainage, down to the condition where the soil exhibits a sharp change in bearing value, or what might be called about the optimum moisture condition. What I am thinking is to get at this thing in a practical way, namely, the extent to which under-drainage can be used as a corrective of part if not all of those soil conditions which have an inefficient bearing value. I have had the feeling for a long while, in watching roads and studying soils, that road engineers generally have not appreciated the fundamental importance of these moisture relations in soils which this paper deals with and I am delighted to see that highway engineers have made a beginning in that direction.

Mr. Marston. MR. ANSON MARSTON.—I want to say that certain work is being done at Ames, Iowa, on a very limited number of soils, on which the tests described in this paper are being carried out according to the same methods (and certain other tests along somewhat similar lines recommended by other authorities), while at the same time, we are determining some of the engineering constants of the soil in place. We are determining, for example, the capacity under different heads to transmit water through the actual soil as it exists in the field. We are determining the coefficients of internal friction of the granular material, a constant which enters into a number of quite important formulas. We are determining the compressive, tensile and shearing strengths of prisms of soil, taken in situ in the field, in comparison with other tests made on limited areas of undisturbed soil in place, in the field, determining the time-settlement curves for different loads.

Mr. Marston. We are determining the porosity, specific gravity, chemical and mineral composition and even the electrical resistance of the soil. These tests are being made in a preliminary, exploratory way. The first season's work was reported in part by the Soils Committee of the American Society of Civil Engineers, January, 1922. It is expected that our work will continue a number of years.

Mr. Goldbeck. MR. A. T. GOLDBECK.—There is one point that has not been fully developed, and that is the possibility of increasing the bearing value of subgrade materials by the use of an admixture. There are certain parts of the country where there are not available any coarse materials, such as sand and gravel, and we know we can increase the bearing value of soils by such admixtures. We have had recently an inspection report from one of our engineers, with reference to one of our cooperative experimental roads in California. It appears they have treated the adobe subgrade in this case with an admixture of portland cement; they have simply spread the cement over the dry subgrade and have harrowed it in the proportion of one part of cement to twenty parts of the adobe soil to a depth of 12 in., and also 6 in. During the winter, of course the subgrade got very wet and the inspection report states that the untreated adobe subgrade was practically impassable, whereas, the cement treated subgrade was hardly marred. Now certain laboratory experiments indicate that other materials might be available for admixtures. I believe that hydrated lime will serve the same purpose. There is a possibility of the use of bituminous materials. For instance, some of our laboratory experiments indicate that admixtures of water-gas tar will increase the bearing value of the soil and change its characteristics so that soils previously plastic become non-plastic. There is an undeveloped field in the treatment of subgrade materials and you can see that there are economic possibilities, because if we can increase the bearing value of the subgrade materials, we can at the same time lighten the design of the road.

Mr. Fippin. MR. FIPPIN.—In what I have to say, I hope I shall not be accused of having put forward propaganda. Some of these people know whom I represent. In the first place, the effect of lime on a soil is to so change its structure as to greatly increase the freedom with which moisture flows through it. In the second place, there are very few chemical materials, taking soils as a whole, that have the high granulating effect that lime has. In the third place, we have recently analyzed rather carefully some data from England which comes from the agricultural side, in which the soils were limed in one case and not limed in the other. The effect of the lime on the physical character of the soil was measured by plowing those soils with an ordinary

Mr. Fippin.

moldboard plow and tractor, with a dynamometer intercepted. It was found that the soil, at a given time after a rain or under normal moisture conditions, was plowed at a 26 per cent greater rate where it was limed than where it was not limed. It was also observed that on the limed soil, which to all appearances was dryer, the tractor did not cut into the soil so much as on the unlimed soil, and the increase in speed was credited to this fact, which is another aspect of the bearing value of soil. I think these two types of treatment of subgrade material, namely, liming to increase the rate of percolation and artificial drainage to remove the excess water above capillary saturation are the means that must be most depended upon to improve the bearing value of the road bed.

AN IMPACT TEST FOR GRAVEL.

By F. H. Jackson.[1]

The test described in this paper supplies, the writer believes, a growing demand among highway engineers for a simple yet fairly reliable method of determining the quality of gravel aggregates. Both producers and users of this material know that gravels from many deposits otherwise satisfactory often contain enough excessively soft and unsound fragments to make their use inadvisable in concrete road construction. In the absence of specific tests, however, it is very difficult to draw a definite line of demarcation between satisfactory and unsatisfactory quality so that when it comes to the actual acceptance or rejection of materials the engineer must fall back upon his own judgment—a doubtful method at best.

Although we have used for many years a number of more or less satisfactory tests for determining the quality of rock to be used in road construction, there has been, so far as the writer is aware, only one method used for making the corresponding tests on gravel. This is the modified Deval abrasion test devised by Rea[2] several years ago and used to a considerable extent in a number of laboratories. The results of a large number of tests made in the laboratory of the Bureau of Public Roads on gravels from every section of the country indicate that, for general application, this test is not particularly satisfactory. In the first place, it measures the *average* loss by abrasion of a large number of pieces which, individually, may and often do vary greatly in hardness and in toughness. Misleading results have sometimes been obtained for this reason, because, although a considerable proportion of a sample may be very poor in quality the balance may be composed of fragments hard enough and tough enough to raise the average loss above the specification requirement. On the other hand, certain types of quartz gravels which show extremely high losses when subjected to this test due to the severe impact action of the six cast-iron balls composing the charge, are still sufficiently sound for use as aggregates in concrete pavements. Another frequent source of trouble with the modified abrasion test is that the loss by abrasion will depend to a large extent on the shape of the particles composing the test charge. This is particularly noticeable if the sample to be tested contains a considerable proportion of oversize pieces which have been run through a crusher and is due to the severe action of the abrasive charge on the sharp edges produced by crushing. The presence of any considerable number of these crushed gravel fragments in a sample has frequently caused as much as 50 to 75 per cent increase in the amount of wear. The writer calls attention to these weaknesses in the abrasion test for gravel simply for the purpose of showing the danger of attempting to make the test of general application. Applied to gravel of a particular type and used by experienced laboratory operators the test has been of value.

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[1] Senior Assistant Testing Engineer, Bureau of Public Roads, U. S. Department of Agriculture.

[2] A description of this test may be found in *Bulletin 949*, U. S. Department of Agriculture, p. 3.

There is some question, however, whether any test at all for abrasion is necessary in the case of gravel aggregates. Laboratory investigations by Abrams[1] indicate apparently that the wear of concrete is not dependent as much on the quality of the coarse aggregate as has been commonly supposed. Observations of gravel aggregate concrete roads under traffic have shown likewise in almost all cases that the actual wear on the pavement is practically negligible. An action which is much more frequently noted is the pitting of the surface of a concrete road due to the breaking up of excessively soft or unsound pieces in the aggregate, which, in the process of finishing, invariably find their way to the surface of the pavement. This is the material (shale, decomposed granite, very soft sandstone, etc.) that we want to detect and reject, and the writer believes that a simple impact test such as is here described will answer the purpose. Although called an impact test, however, it must be understood that there is no attempt made to determine the actual resistance to impact or toughness of individual fragments in the same sense that a toughness test of rock is made. In the first place, due to the many variables present, it is next to impossible to do this, and in the second place, even if it were possible, it would not, in the writer's opinion, be necessary. The test, therefore, is designed simply to differentiate between satisfactory and unsatisfactory materials as measured by the ability of each fragment to withstand a single blow of a hammer of known weight, the height of fall being such that only very soft or unsound, decomposed pieces will fracture. In other words, the test simply attempts to define in terms of numerical values the usual specification phrase "shall be composed of sound, hard, durable particles."

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[1] D. A. Abrams, "Wear Tests of Concrete," *Proceedings*, Am. Soc. Test. Mats., Vol. 21, p. 1013 (1921).

DESCRIPTION OF APPARATUS.

The apparatus, a view of which is shown in Fig. 1, consists essentially of two $2\frac{1}{2}$-in. steel balls, the lower ball fastened rigidly to a cast-iron anvil measuring 5 in. in diameter by $1\frac{3}{4}$ in. high and the upper one free to fall between three $\frac{3}{8}$-in. guide rods. An adjustable stop, provided with a clamping nut, slides on one of the guide rods. Fastened rigidly to the upper ball is a $\frac{3}{8}$-in. rod graduated in inches, which passes through a hole in the stop. The hammer, consisting of the upper ball and the graduated rod, weighs exactly 1200 g., while the remainder of the apparatus weighs exactly 6 kg., so that the ratio of the weight of the hammer to the weight of the anvil is 1 to 5.

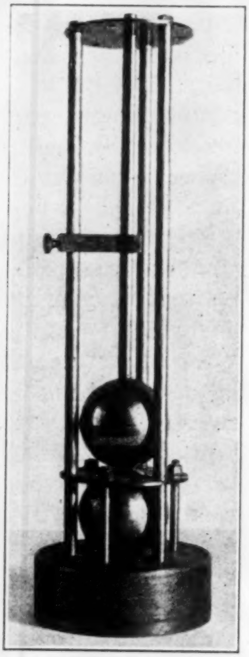


FIG. 1.—View of Impact Machine.

The operation of the test is extremely simple. The fragment to be tested is held firmly on the lower ball between the thumb and the first finger of the right hand so that its smallest diameter is vertical. The upper ball is then allowed to rest on the test specimen and the stop adjusted at the height of fall desired, measured in inches directly on the rod. The stop is then clamped in position, the upper ball raised until in contact with it and allowed to fall upon the specimen. A very little practice will make an operator adept in holding the specimen in place without difficulty. It is possible also in almost every case to secure a reasonably firm bearing on the lower ball. This may be done by trying the specimen in various positions, allowing the ball to drop in each case from a very small height, say $\frac{1}{4}$ in., and noting the effect.

The relative height of fall for fragments of various diameters has been determined tentatively in the following manner:

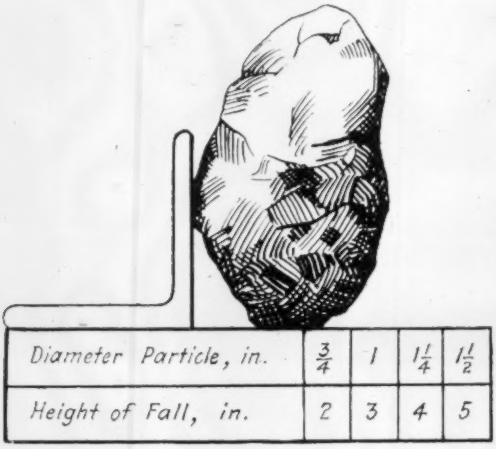
A large quantity of soft limestone of uniform quality was obtained. When subjected to the usual stone tests, this sample showed a percentage of wear of 11.0, a toughness of 3, and a hardness of 8.0. The material was broken by hand into pieces approximately 2 in. in diameter and under, and then run in the Deval abrasion machine until all the fragments had become rounded. This produced an artificial gravel of uniform quality and yet one which was obtained from rock too soft for use as concrete aggregate. The material was then divided into various groups of sizes differing in minimum diameter by $\frac{1}{4}$ in. as follows: Size No. 1 was composed of pieces, the minimum diameter of which varied from $1\frac{3}{8}$ to $1\frac{5}{8}$ in.; size No. 2 from $1\frac{1}{8}$ to $1\frac{3}{8}$ in.; size No. 3 from $\frac{7}{8}$ to $1\frac{1}{8}$ in.; and size No. 4 from $\frac{5}{8}$ to $\frac{7}{8}$ in. Fifty pieces of each size were selected and the height of blow required to fracture each was determined. These values were obtained by subjecting each specimen to a blow from a height of 1 in. and then increasing the height of fall by 1-in. increments until failure. The average results for each size of particle are as follows:

SIZE No.	MINIMUM DIAMETER, IN.	AVERAGE HEIGHT OF BLOW AT FAILURE, IN.
1........	$1\frac{1}{2}$	5.2
2........	$1\frac{1}{4}$	4.1
3........	1	3.0
4........	$\frac{3}{4}$	2.1

These figures seem to indicate that for a material of uniform quality a fairly definite relation exists between the height of fall and the diameter of the particle. Having established this relation, the next step is to determine the proper height of fall which, for particles of a given size, will fracture only unsound or otherwise objectionable pieces. This can only be done after considerable further experimentation. A tentative method of test has been decided on, however, using the values given in the table above with the understanding that they may be modified later if necessary.

TENTATIVE METHOD OF TEST.

The material to be tested is accurately quartered down until a sample is obtained which contains from 25 to 50 pieces ranging in size from $\frac{3}{4}$ to 2 in. in diameter. Care should be taken to see that the various sizes appear in about the same proportion as in the original sample. The pieces thus obtained are then tested individually by first determining the average diameter across the shortest dimension and then subjecting each to a single blow of the hammer from the height called for in the table. Flat pieces whose longest diameter is over three times their shortest diameter are not tested. A convenient scale for measuring the diameter of a particle is shown in Fig. 2. In using this scale, a fragment is held against the stop so as to measure its least diameter along the upper scale. The proper height of fall is then read directly on the lower scale. The average time required to test a sample by this method is approximately twenty minutes.



Diameter Particle, in.	$\frac{3}{4}$	1	$1\frac{1}{4}$	$1\frac{1}{2}$
Height of Fall, in.	2	3	4	5

FIG. 2.—Scale for Determining Height of Hammer Blow for Particles of Various Diameters.

A number of gravels of various types have been tested with this apparatus and the results so far seem to indicate that the instrument will serve the purpose for which it was designed. It must be borne in mind, however, that the limits set in the table are purely arbitrary and may have to be modified after further experimentation. The point to be emphasized is that the energy of the blow to be delivered must be just great enough to fracture unsound or disintegrated fragments. For this reason the limits set in Table I, based on the use of very soft stone, appear to be on the safe side.

A point in connection with the test which has not yet been worked out is the question of the allowable percentage of soft pieces in gravel aggregate. The Bureau of Public Roads hopes to obtain considerable information which will assist in determining this limit during the present season in connection with an accelerated wear test now under way at Arlington, Va. As a part of this experiment a number of concrete sections containing gravel aggregates of various types are being studied and their behavior under test should materially assist in establishing a specification limit of allowable percentage of soft pieces as measured by the proposed test.

CONCLUSION.

In conclusion, the writer would like to call attention again to the need for a simple test for quality of gravel aggregates such as the one described. The question of utilizing local sources of supply for concrete aggregates has been much discussed of late. There can be no question of the desirability of utilizing such material provided some assurance may be had that aggregate of suitable quality will be obtained. A test of this nature which can be made either in the laboratory or by the prospector at the pit should assist in solving the problem, especially if, as the writer believes, the experiments on wear now being carried out by the Bureau of Public Roads will show that the factor of prime importance in studying gravel aggregates is not resistance to wear as measured by an abrasion test but is rather uniformity in quality as measured by freedom from soft, unsound or disintegrated stone.

DISCUSSION.

Mr. Purrington.

Mr. W. F. Purrington (*presented in written form*).—The new impact test for gravel which is so ably described in Mr. Jackson's paper has a great many things to be said in its favor. Mr. Jackson states that the method outlined is only tentative. Presumably, he has worked more especially upon gravels formed from rocks of igneous sedimentary origin and of nearly uniform texture. In order to use this test upon gravels composed of rocks of metamorphic origin modifications appear necessary.

In the first place, the height of fall is not sufficient to break most of those pieces which are without question disintegrated. In studying Jackson's method recently, the height of fall for each measurement was increased one inch without securing more breaks than seem desirable.

Further, the method calls for the use of from 25 to 50 pieces. To make the method more accurate 100 pieces would seem to be preferable, in spite of the greater time required to test them.

The following study of typical New Hampshire gravels has been made with results which are given in detail in Table I.

The gravels containing the schists and those containing Canaan granite, which is gneissic, would have registered more breaks if the blow had been made in the direction of the grain, instead of transverse to it. The method used for the abrasion test was the one described in the U. S. Department of Agriculture *Bulletin No. 949*, page 3, with the unslotted cylinder.

The rule discarding pieces whose longest diameter is over three times their short diameter eliminates many of those stones which are most likely to fail, that is, those stones with marked foliation. The weakness in the stones is seen either in (*a*) a crumbling apart of the component crystals which in non-foliated rock may occur in one direction as well as another, or (*b*) in the splitting of rocks which have a definite grain along these planes. Such rocks, especially the schists, slates and other metamorphic rocks which are abundant in the northeastern states split readily when struck in the direction of the grain but not when struck across the grain, that is, in the direction of the shortest diameter as Jackson requires.

TABLE I.—RESULTS OF IMPACT TESTS ON GRAVELS.

	Number of Pieces of a Given Kind of Rock.		Number of Pieces Broken.		Percentage Broken of Stones of a Given Size.							
					First Fifty.				Second Fifty.			
	First Fifty.	Second Fifty.	First Fifty.	Second Fifty.	$\frac{3}{4}$ in.	1 in.	$1\frac{1}{4}$ in.	$1\frac{1}{2}$ in.	$\frac{3}{4}$ in.	1 in.	$1\frac{1}{4}$ in.	$1\frac{1}{2}$ in.
GRAVEL NO. 1. (WEAR, 8.8 PER CENT.)												
Crystallin Schists	35	41	4	10	16	0	20	0	41	10	25	0
Granite (Concord)	3	9	0	1	0	0	0	0	33	0	0	0
Felsites	2	0	0	0	0	0	0	0	..	..	..	..
Total	50	50	4	11								
Per cent broken	..	..	8	22								
GRAVEL NO. 2. (WEAR, 14.4 PER CENT.)												
Granite Porphyry	32	33	14	13	40	60	30	0	55	25	25	0
Granite (Canaan)	11	4	6	1	50	60	0	0	0	100	0	0
Miscellaneous	7	13	1	6	25	0	0	0	28	0	50	0
Total	50	50	21	20								
Per cent broken	..	..	42	40								
GRAVEL NO. 3. (WEAR, 8.8 PER CENT.)												
Granite (Concord)	34	32	0	1	0	0	0	0	4	0	0	0
Crystallin Schists	15	18	3	1	0	23	0	0	0	33	0	0
Vein Quartz	1	0	0	0	0	0	0	0	..	..	..	..
Total	50	50	3	2								
Per cent broken	..	..	6	4								
GRAVEL NO. 4. (WEAR, 18.9 PER CENT.)												
Granite (Canaan)	39	39	8[a]	18	13	35	14	20	30	77	31	0
Miscellaneous	11	11	0	1	0	0	0	0	25	0	0	0
Total	50	50	8	19								
Per cent broken	..	..	16	38								
GRAVEL NO. 5. (WEAR, 11.6 PER CENT.)												
Granite (coarse)	21	..	7	..	30	40	33	0	..	..	..	..
Granite (fine)	10	..	3	..	14	66	0	0	..	..	..	..
Felsite	19	..	3	..	14	25	0	0	..	..	..	..
Total	50		13									
Per cent broken	..	..	26									

[a] With the exception of this sample, the height was increased 1 in. above the limits set by Jackson for all width of pieces.

Mr. Purrington. The purpose of this test is to eliminate poor stones. As applied to New England gravels it does not sufficiently do this; for the poorest stones are oftentimes the flattish ones with cleavage and these either are not to be tested because of the 1 : 3 ratio, or if tested, are struck perpendicular to the cleavage, that is to say, in the direction in which they are least likely to split.

Mr. Crum. MR. R. W. CRUM.—It appears to me that this is a very promising line of investigation. I heartily agree with Mr. Jackson that a study of the constituent particles of gravel for coarse aggregate will be more productive of results than tests on full samples. I wish, however, to call attention to what appears to me to be a weakness in the test in that it only applies to fairly large sized material, whereas in many gravels of glacial origin there is bound to occur considerable of the rotten, soft and partially disintegrated particles, ranging in size from ¼ to ½ in. I hope that continued study will take this fact into account, and I have no doubt that the test can be strengthened to take care of the entire range of sizes in our ordinary gravels.

Mr. Abrams. MR. D. A. ABRAMS (*by letter*).—We have been carrying out in our laboratory in Chicago two lines of investigations which have a bearing on the questions raised by Mr. Jackson's paper:

(1) Crushing tests of graded aggregates.

(2) A detailed study of various methods of making wear tests of aggregate by means of the Deval abrasion machine.

1. *Crushing Tests of Graded Aggregates.*—The crushing test is an adaptation of a method used in Austria.[1] A sample of graded aggregate is placed in a cast-iron vessel (Fig. 1) and subjected to pressure through a loose-fitting plunger.

Table II shows how the test may be used in a study of different types of aggregate. A 3000-g. sample was placed in the 30-sq.-in. cylinder and a load of 3000 lb. per sq. in. applied by means of a testing machine. All samples had the following grading:

No. 4 to ⅜-in.	25	per cent	(by weight).
⅜ to ¾-in.	50	"	"
¾ to 1½-in.	25	"	"

The crushing produced is measured by comparing the sieve analysis before and after test. The difference in fineness modulus may be taken as a measure of the crushing produced. The fineness modulus is a yard-stick which can be used for measuring the size and grading of any granular material; it is the sum of the percentages in the sieve analysis, divided by 100. The sieve analysis is expressed

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[1] *Proceedings*, Int. Assn. Testing Mats. (1912) ,2d Section, Paper XXVI$_1$*a*.

Mr. Abrams. in terms of the percentages *coarser than* each of the following sieves:[1] No. 100, 50, 30, 16, 8, 4, and $\frac{3}{8}$, $\frac{3}{4}$, $1\frac{1}{2}$-in., etc.

This test would place these materials in the order: trap, pebbles, granite, limestone, slag, and sandstone.

The relative behavior of rounded and angular particles is shown by the single test of Chicago crushed limestone compared with the same material after it had been run in the Deval abrasion testing machine for 20,000 revolutions. The angular particles gave a difference in fineness modulus of 1.34 and the rounded ones 1.03. Pebbles from Elgin, Ill. (of limestone origin), gave almost the same result as the rounded limestone.

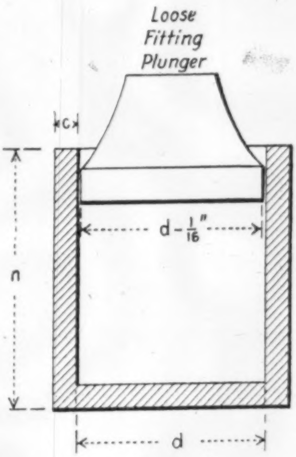

FIG. 1.—Apparatus for Crushing Tests of Aggregate.

AREA, SQ. IN.	DIAMETER (*d*), IN.	DEPTH (*h*), IN.	WALL THICKNESS (*c*), IN.
50	8.0	10.5	0.9
40	7.2	9.6	0.9
30	6.2	8.3	0.8
20	5.1	6.2	0.6
10	3.6	4.9	0.5

The following topics have been studied by this method:

(*a*) Size of cylinder;
(*b*) Size of sample;
(*c*) Grading of aggregate;
(*d*) Pressure used;
(*e*) Rate of application of load;
(*f*) Type of aggregate.

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[1] See Tentative Method of Test for Sieve Analysis of Aggregates for Concrete (C 41 – 21 T), *Proceedings*, Am. Soc. Test. Mats., Vol. 21, p. 586 (1921).

TABLE II.—CRUSHING TESTS OF CONCRETE AGGREGATES.

3000-g. samples graded No. 4 sieve to 1½ in.
30-sq. in. cylinder used.
Pressure, 3000 lb. per sq. in.
2 or more tests made on each sample.

Aggregate.	Number of Samples.	Average Sieve Analysis[1] of Aggregates after Test.									Fineness Modulus.	Difference in Fineness Modulus Due to Crushing.
		No. 100	No. 50	No. 30	No. 16	No. 8	No. 4	$\frac{3}{8}$-in.	$\frac{3}{4}$-in.	1-$\frac{1}{2}$ in.		
All aggregates *before* test	..	100	100	100	100	100	100	75	25	0	7.00	....
Pebbles	9	97	95	94	86	84	73	47	13	0	5.89	1.11
Limestone	9	96	93	90	85	75	63	37	12	0	5.51	1.49
Trap	6	98	97	96	93	84	73	46	14	0	6.01	0.99
Granite	6	96	94	91	87	76	64	38	12	0	5.58	1.42
Slag	10	95	92	87	82	71	60	36	10	0	5.33	1.67
Sandstone	7	92	84	75	72	65	58	36	11	0	4.93	2.07
Limestone (Chicago)	1	96	95	92	88	77	65	41	12	0	5.66	1.34
Limestone (Chicago)[2]	1	97	96	93	90	83	72	46	20	0	5.99	1.03
Pebbles (Elgin, Ill.)	1	97	96	97	91	84	72	46	15	0	5.95	1.05

[1] Amounts coarser than each sieve—per cent by weight.

[2] Particles rounded by running in Deval abrasion testing machine for 20,000 revolutions before crushing test was made.

TABLE III.—EFFECT OF SHAPE OF PARTICLES ON WEAR OF AGGREGATE.

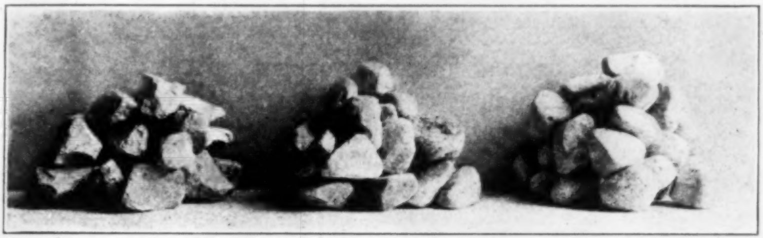
Tests made in a standard Deval abrasion machine.
Standard sample made up of 50 pieces weighing 5000 g.
Machine run for 10,000 revolutions at about 33 r. p. m.

Kind of Aggregate.	Wear, Percentage by Weight Finer than No. 16 Sieve.							
	First Test.	Second Test.	Third Test.	Fourth Test.	Fifth Test.	Sixth Test.	Seventh Test.	Eighth Test.
Crushed Limestone (Chicago)	3.82	2.86	....	....	....	....	....	....
	3.86	2.66	2.22	1.76	....	....	....	....
	3.90	3.04	2.94	2.20	1.88	1.68	1.36	1.44
	3.88	3.04	2.26	2.00	1.74	1.68	2.04	1.28
Average	3.86	2.80	2.44	1.99	1.81	1.68	1.70	1.36
Crushed Slag (Chicago)	7.38	....	....	....	....	....	....	....
	7.24	4.00	2.80	....	....	....	....	....
	7.68	3.68	2.74	2.30	2.60	2.04	....	....
	7.50	3.60	2.86	2.50	2.20	2.20	2.00	1.92
Average	7.45	3.76	2.80	2.40	2.40	2.12	2.00	1.92
Pebbles[1] (Elgin, Ill.)	1.94	1.74	....	....	....	....	....	....
	1.86	2.00	1.60	1.60	1.64	1.30	....	....
	2.06	1.80	1.70	1.60	1.56	1.40	1.36	....
	2.29	1.74	1.60	1.60	1.08	0.92	1.46	....
Average	2.08	1.82	1.63	1.60	1.43	1.21	1.41	
Crushed Sandstone (Kettle River, Minn.)	11.50	....	....	....	....	....	....	....
	11.56	7.70	....	....	....	....	....	....
	12.10	5.20	5.60	5.34	....	....	....	....
	11.20	8.66	6.30	4.56	5.54	5.60	....	....
Average	11.59	7.19	5.95	4.95	5.54	5.60	....	....
Crushed Granite (Wisconsin)	1.70	....	....	....	....	....	....	....
	1.78	0.56	0.40	....	....	....	....	....
	1.64	0.80	0.56	0.34	0.32	....	....	....
	1.72	0.60	0.40	0.46	0.32	....	....	....
Average	1.71	0.65	0.45	0.40	0.32	....	....	....

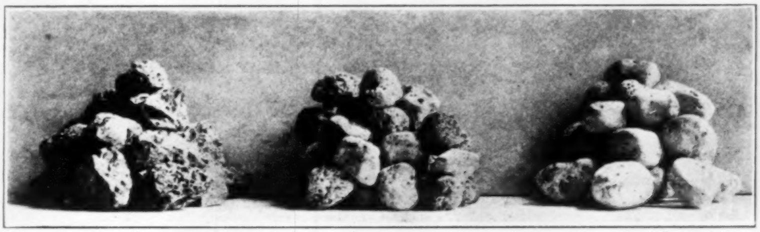
[1] Pebbles of limestone origin.

Mr. Abrams. Cylinders having cross-sectional areas of 10, 20, 30, 40, and 50 sq. in. have been used. The size of cylinder makes little difference so long as it is not too small as compared with the size of the aggregate.

2. *Effect of Shape of Particles on the Wear of Aggregates.*—The purpose of the tests in Table III was to study the wear of aggregates of different types after the crushed particles had been worn to a rounded form. All tests were made in the Deval abrasion machine in accordance with the Standard Method of Test for Abrasion of Road Material (Serial Designation: D 2 - 08) of the American Society for Testing Materials.[1] Four standard samples of each aggregate were run at first in order to secure a sufficient quantity for the later tests.



(*a*) Before Testing. (*b*) After 1 test. (*c*) After 8 tests.
Crushed Limestone.



(*d*) Before Testing. (*e*) After 1 test. (*f*) After 8 tests.
Crushed Blast-Furnace Slag.

FIG. 2.—Samples of Aggregates Used in Deval Tests.

Fig. 2 shows the shape of particles of limestone and crushed slag before testing and after the corners had been rounded off. It should be pointed out that this photograph shows only the large-size particles, similar to those used in the standard sample.

The average percentage of wear of limestone pebbles for the fifth to seventh test is almost the same as for the crushed limestone at

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[1] 1921 Book of A.S.T.M. Standards, p. 710.

Mr. Abrams. the eighth test, although the latter value is only 35 per cent of the former in the first test.

It is significant that the *order* of values for the different aggregates is the same in the fifth as in the first test.

It is probable that the particles used in the later tests represented the *hardest* and *toughest* of the original samples.

In addition to the wear tests described above, we have studied the following:

(*a*) Effect of grading of aggregates;
(*b*) Effect of size of sample;
(*c*) Use of slotted cylinder;
(*d*) Effect of number and size of shot;
(*e*) Effect of number of revolutions;
(*f*) Wear tests of many coarse aggregates.

A more detailed report of both the crushing and wear tests of aggregate is in preparation.

THE USE OF EXCESS SAND AND PIT-RUN GRAVEL IN CONCRETE PAVEMENTS.

BY R. W. CRUM.[1]

FIELD TESTS.

Although the paper on "Proportioning of Pit-Run Gravel for Concrete,"[2] presented by the author at the 1919 annual meeting of the Society, referred only to the use of pit-run material, it has been found economical in many cases to use the method proposed therein, for proportioning mixtures of screened sand and gravel containing various ratios of sand to gravel. This paper covers the use of this method of proportioning upon 122 miles of pavement laid under the supervision of the Iowa State Highway Commission during 1920 and 1921, as compared with 65 miles in which the proportions of 1 : 2 : 3.5 by volume were arbitrarily specified. Pit-run gravel was used in 35.43 of the 122 miles.

The necessity for the use of relatively large ratios of sand to coarse aggregate arises from the fact that the entire gravel supply of Iowa contains from 50 to 85 per cent of material finer than the opening in a No. 4 sieve (sand). Inasmuch as the general construction demand for sand is not large enough to absorb the excess of sand, proper engineering methods must be employed to prevent the waste of vast quantities of valuable material. The proper economical and engineering solution of the construction problems in the State of Iowa require the use of all of our available materials. It appears probable in connection with highway construction that after the other demands for sand are satisfied that an aggregate containing half sand and half coarse aggregate will be in rather general use.

The comparisons and conclusions based thereon are based upon the tests of specimens made during the progress of the work. Two 6 by 12-in. cylinders and two 8 by 8 by 5-in. blocks for the Talbot-Jones wear tests were made each day, and stored along the road for curing under substantially the same conditions as the pavement itself. Information as to the uniformity of the mixtures was secured by washing the cement from a sample of the concrete from the same batch as the cylinders, and running a sieve analysis upon the aggregates.

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[1] Engineer of Materials and Tests, Iowa State Highway Commission.

[2] R. W. Crum, "Proportioning of Pit-Run Gravel for Concrete," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II, p. 458 (1919).

It is to be expected of specimens and analyses made in this way under field conditions that there will be considerable variation in individual results. However, if a considerable number of specimens are used, it is reasonable to expect that the averages will actually represent the qualities of the concrete and that the variation in individuals will give some measure of comparative uniformity.

In addition to the specimens made during construction, cylinders were taken from the pavement on several projects after the pavement had been in use for from 6 to 12 months. In each case the cores were taken from a spot in the pavement which was represented by specimens made during construction.

TABLE I.—TYPICAL PROPERTIES OF MATERIALS, PAVEMENT CONSTRUCTION, 1920.

Project No.	Material.	Sieve Analysis, per cent passing									Silt, per cent.	Rotten Stone, per cent.	Shale, per cent.	Limestone, per cent.	Hardstone, per cent.
		$1\frac{1}{2}$-in.	$\frac{3}{4}$-in.	$\frac{3}{8}$-in.	No. 4	No. 8	No. 14	No. 28	No. 48	No. 100					
1	Pit-run Gravel	100	88.0	73.0	60.0	50.1	40.0	26.0	7.5	1.25	2.72	2.6	0.0	59.0	38.4
2	Pit-run Gravel	100	91.5	84.0	72.0	58.0	41.0	21.5	2.66	1.00	0.60	0.10	0.25	50.0	50.0
3	Sand	....	....	....	98.0	80.1	61.0	35.0	7.0	1.00	0.65	1.00	0.0	25.0	75.0
	Gravel	100	67.0	40.0	5.0	....	....	....	....	....	....	....	0.2	23.0	75.0
	Pit-run Gravel	100	82.4	67.9	51.5	38.6	26.7	13.9	2.20	0.40	0.50	1.00	0.0	19.0	80.0
4	Sand	....	....	....	99.0	80.1	60.2	35.0	7.0	1.75	1.00	0.50	Trace	24.5	75.0
	Gravel	93	61.0	25.0	7.5	....	....	....	....	....	....	1.95	Trace	23.0	75.0
5-7-8-9-10-11-12	Sand	....	....	....	96.0	81.8	50.4	20.8	6.6	2.4	1.6	0.8	Trace	....	....
	Gravel	87.0	57.0	24.0	4.0	....	....	....	....	....	....	1.0	Trace	44.0	55.0
6	Sand	....	....	....	100	88.0	69.0	30.5	6.5	1.5	1.5	1.5	0.0	....	98.5
	Gravel	95.0	53.0	15.0	1.5	....	....	....	....	....	....	1.5	0.0	....	98.5
10	Sand	....	....	....	96.5	78.0	60.7	38.0	7.2	2.0	3.0	1.0	....	45.0	45.0
	Gravel	98.5	70.0	30.1	4.5	....	....	....	....	....	3.0	1.0	....	49.0	50.0
13	Sand	....	....	....	96.4	81.7	57.6	28.9	6.0	1.0	1.33	1.0	0.2	42.7	56.6
	Gravel	100	62.0	28.0	7.0	....	....	....	....	....	....	....	....	....	....
14	Sand	....	....	....	99.5	92.2	81.7	53.2	9.0	1.2	2.0	1.2	....	....	....
	Limestone	100	45.0	16.0	3.0	....	....	....	....	....	....	....	....	100	....
15 and 16	Pit-run Gravel	100	89.0	79.0	69.4	60.7	50.0	21.5	5.2	1.2	....	....	....	....	....
	Limestone	100	45.0	16.0	3.0	....	....	....	....	....	....	....	....	100	....

NOTE.—Very similar materials were used in 1921.

The data obtained are shown graphically in Figs. 1 to 4, inclusive.

UNIFORMITY OF COMPOSITION.

Sieve Analysis.—Other qualities being equal, the principal objection to the use of pit-run gravel has been the fancied lack of uniformity in the resulting concrete. It is true that these experiments show that there is a great opportunity for improvement in the uniformity of concrete mixes, but, it is rather surprising to note that the mixtures of screened aggregates are no better in this respect than pit-run gravel mixtures, and often not so good when the pit-run gravel is handled in the most advantageous manner.

Fig. 5 shows the variation in composition on the various jobs as indicated by the sieve analyses made each day upon samples taken direct from the pavement. The diagram shows the maximum and minimum percentage of sand in the aggregate for the entire job, and the percentage of sand upon which the proportions were based. It is interesting to note in this connection that in every case in which the percentage of sand was less than the base the cement content was correspondingly higher than necessary and the resulting concrete was therefore somewhat better than expected. This shows at least one obvious advantage in the use of excess sand mixtures.

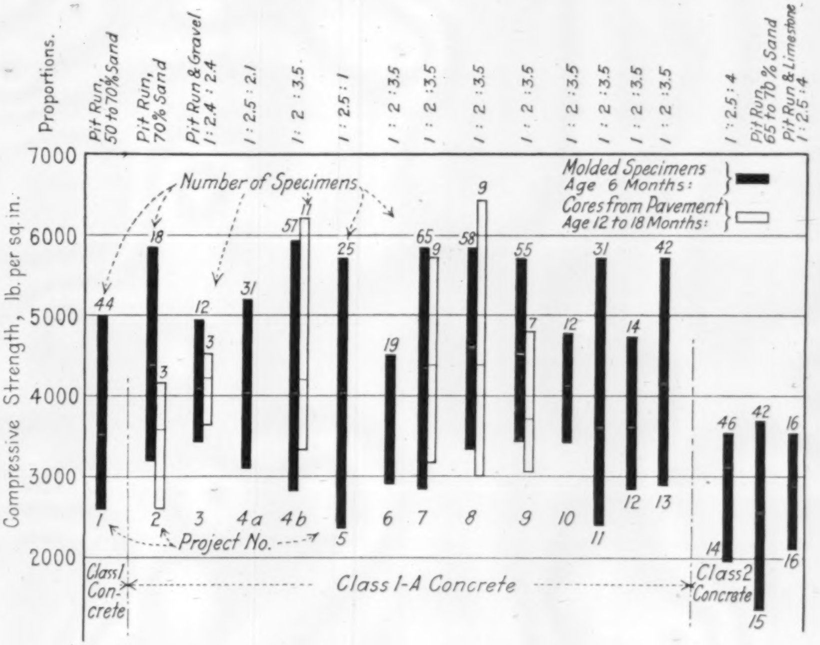

FIG. 1.—Compressive Strength of Field Specimens, Showing Maximum, Minimum and Average Strengths. Pavement Construction, 1920.

LABORATORY INVESTIGATIONS.

Transverse Tests.—Laboratory tests were made to verify the application of the "sand" method of proportioning, on the strength of concrete in transverse tests, and also to study the extension of the method to cover mixtures of sand and crushed limestone. The results show that equivalent transverse strength can be secured by this method and that the method applies to the use of crushed limestone.

Twelve proportions, three consistencies and two types of materials were used, ten specimens being made for each mixture. Six hundred and eighty specimens were made and tested at the age of 28 days.

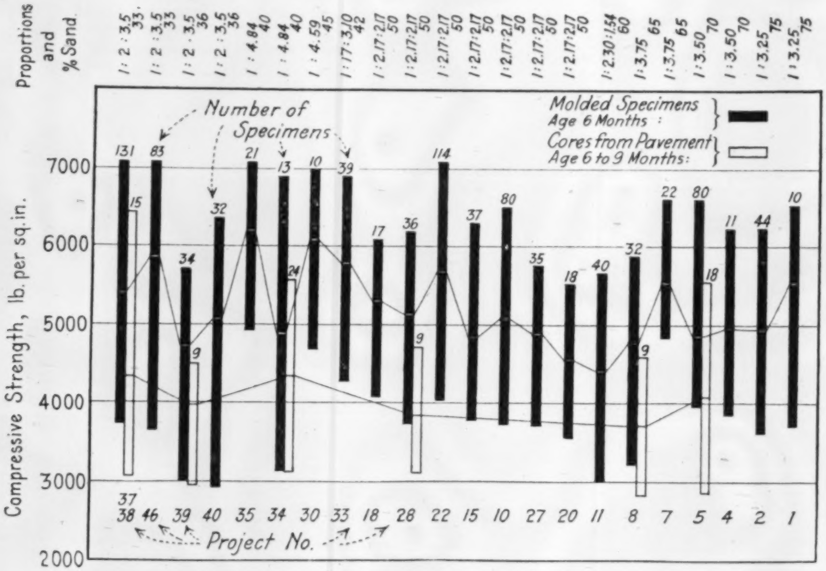

FIG. 2.—Compressive Strength of Field Specimens, Showing Maximum, Minimum and Average Strengths. Pavement Construction, 1921, Class 1A Concrete.

Storage was in damp sand. The beams were all 4 by 8 by 30 in. Characteristics of the materials used are shown in Table II.

Table III gives the data concerning these specimens. Figs. 6 and 7 show the relationship of the various factors graphically.

CONCLUSIONS.

In view of the experience recorded herein, the Iowa State Highway Commission has based the standard specifications for single-course concrete pavement upon the assumption that it is possible to so design and construct concrete pavements with varying cement, sand, and coarse aggregate contents that the results will be in as close agreement as may be expected from the arbitrary mixtures in common use.

TABLE II.—PHYSICAL CHARACTERISTICS OF AGGREGATES USED IN LABORATORY SPECIMENS.

	SAND.	GRAVEL.	CRUSHED LIMESTONE.
Number of tests	12	12	12
Loose weight, lb. per cu. ft	92.1	95.6	82.5
Silt, per cent	1.1	0.46	....
Specific gravity	2.62	2.66	2.55
Sieve analysis:			
Passing sieve, per cent:			
1.5-in	.....	96.46	100.0
0.75-in	.....	32.10	20.89
0.371-in	.....	8.91	6.05
No. 4	99.07	0.96	1.02
No. 8	87.8	....	....
No. 14	70.89	....	....
No. 28	47.23	....	....
No. 48	13.39	....	....
No. 100	2.05	....	....

TABLE III.—TESTS OF BEAMS IN LABORATORY INVESTIGATIONS.

Coarse Aggregate.	Proportion, by Weight.	Density.			Ratio $\frac{\text{Cement}}{\text{Voids}}$, $\frac{c}{1-d}$			Modulus of Rupture, lb. per sq. in.		
		Dry.[1]	Medium.[1]	Wet.[1]	Dry.[1]	Medium.[1]	Wet.[1]	Dry.[1]	Medium.[1]	Wet.[1]
Gravel	1 : 1.71 : 3.47	0.8611	0.8481	0.8230	0.876	0.786	0.665	567	574	467
	1 : 1.93 : 2.91	0.8495	0.8347	0.828	0.833	0.747	0.691	543	554	456
	1 : 2.06 : 2.83	0.8418	0.8294	0.8066	0.811	0.762	0.642	613	547	455
	1 : 2.17 : 2.17	0.8300	0.8171	0.7996	0.797	0.725	0.648	548	570	521
	1 : 2.25 : 1.85	0.8240	0.8104	0.7933	0.796	0.729	0.654	607	550	527
	1 : 2.30 : 1.54	0.8110	0.7984	0.7844	0.768	0.712	0.653	565	548	433
	1 : 2.34 : 1.25	0.8030	0.7897	0.7693	0.773	0.714	0.634	599	530	501
	1 : 2.34 : 1.01	0.7960	0.7825	0.7623	0.781	0.723	0.639	593	568	538
	1 : 2.33 : 0.77	0.7790	0.7755	0.7546	0.763	0.739	0.658	614	553	488
	1 : 2.29 : 0.57	0.7760	0.7650	0.7485	0.791	0.736	0.674	607	583	522
	1 : 2.12 : 0.24	0.7520	0.7411	0.7263	0.794	0.747	0.694	574	595	544
	1 : 1.87 : 0	0.7350	0.7196	0,6990	0.850	0.792	0.719	647	550	574
Limestone	1 : 1.71 : 3.40	0.8535	0.8430	0.8270	0.812	0.759	0.663	498	520	436
	1 : 1.93 : 2.85	0.8505	0.8380	0.8180	0.842	0.769	0.665	591	516	482
	1 : 2.06 : 2.48	0.8379	0.8316	0.8030	0.796	0.764	0.624	568	499	424
	1 : 2.17 : 2.12	0.8330	0.8266	0.8060	0.809	0.773	0.671	565	438	407
	1 : 2.25 : 1.82	0.8223	0.8099	0.7920	0.782	0.719	0.644	572	534	518
	1 : 2.30 : 1.51	0.8130	0.8017	0.7820	0.777	0.721	0.649	560	547	474
	1 : 2.34 : 1.24	0.8035	0.7941	0.7740	0.769	0.726	0.644	528	535	497
	1 : 2.34 : 0.98	0.7903	0.7831	0.7520	0.752	0.724	0.611	569	567	460
	1 : 2.39 : 0.76	0.7785	0.7684	0.7420	0.751	0.703	0.609	554	564	523
	1 : 2.29 : 0.56	0.7710	0.7633	0.7410	0.762	0.728	0.650	533	558	599
	1 : 2.12 : 0.24	0.7487	0.7403	0.7210	0.778	0.744	0.683	613	631	535
							Average	575	549	494

[1] Average Consistency:
Dry, Cone slump, 0 in.; Flow table, 106.
Medium, Cone slump, 1 in.; Flow table, 125.
Wet, Cone slump, 6 in.; Flow table, 188.

The medium consistency compares with that used in pavement construction in Iowa. It is apparently a very reliable consistency.

Furthermore, the more heavily sanded mixtures have at least two important advantages.

1. It is quite generally accepted that if the voids in the coarse aggregate are more than filled by the cement and sand mortar, the internal grading of the coarse aggregate will have little effect upon the strength of the concrete. Such being the case with the mixtures under discussion makes it possible to use certain aggregates which might not be suitable for use in the more common mixes.

2. In proportioning mixes of high sand to coarse aggregate ratio, the amount of the cement should be based upon the maximum amount of sand to be expected; then, when the amount of sand at times becomes less, the high ratio of cement to sand will more than compensate for the variation. For instance, if the proportion be based upon 70 per cent of sand, and the percentage of sand falls to 60, the mix would have more cement than the 60-per-cent sand requires, and the variation would not be at the expense of the strength of the concrete. As shown by the records of actual sieve analyses given in Fig. 5, considerable such variation is to be expected. Mixes, such as the usual 1 : 2 : 4, which are intended to just fill the voids in the coarse aggregate do not provide any such factor of safety and most of the variation is, therefore, more serious.

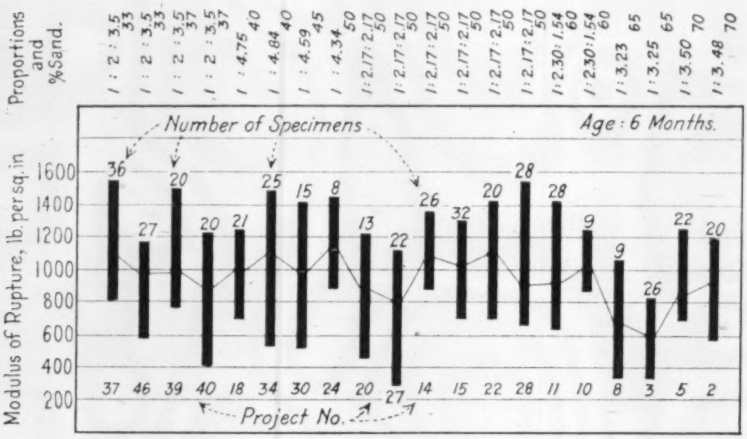

FIG. 3.—Transverse Tests of Field Specimens Showing Maximum, Minimum and Average Strengths. Pavement Construction, 1921.

Control.—A most important factor in the successful use of unusual and varying mixes is the careful and accurate control of the details of construction. This requires two full time inspectors upon the job in addition to the inspection and tests made upon each unit of shipment by the material inspection force. One inspector is constantly on duty at the measuring and proportioning station and the other supervises the placing and curing of the concrete.

Temperature Stresses.—There are some indications that the temperature stresses in mixtures containing above 60 per cent of sand are higher than usual, as evidenced by the number of transverse cracks in the pavement. Data on this point are not now available but the point is under investigation.

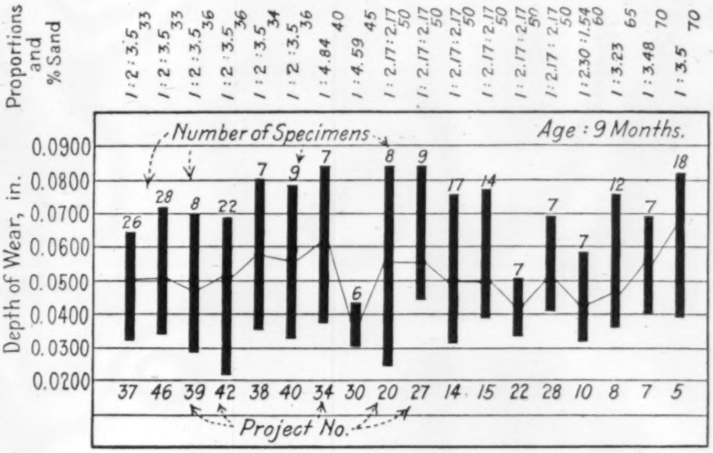

FIG. 4.—Wear Tests of Field Specimens, Showing Maximum, Minimum and Average Wear. Pavement Construction, 1921.

PROPORTIONS FOR CONCRETE PAVEMENT.

The following are the requirements specified by the Iowa State Highway Commission for proportioning concrete for concrete pavements: When a screened or unscreened gravel aggregate is used for either type of pavement, the ratio of cement to the aggregate, by weight, shall be in accordance with Table IV below. The mixtures may be made either by weight or by measure. When volumetric measurements are used, the proper ratios to use will depend upon the weights per cubic foot of the materials and will be established by the engineer. A bag of cement weighing 94 lb. net shall be considered to contain one cubic foot.

If unscreened gravel aggregate is used, either for concrete pavement construction or for concrete base, the proposed source of supply must be approved by the engineer (Highway Commission) before any

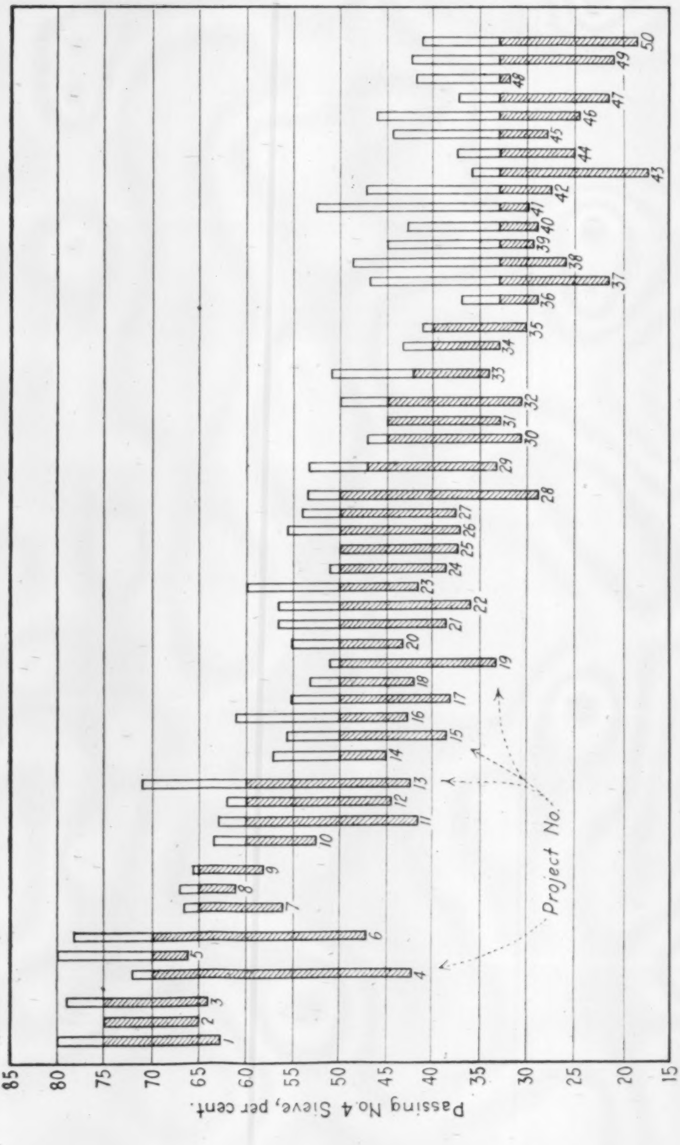

FIG. 5.—Variation in Sieve Analysis Showing Maximum and Minimum Per Cent Passing No. 4 Sieve. Division Line Indicates Per Cent Passing No. 4 Sieve upon which Proportions were based.

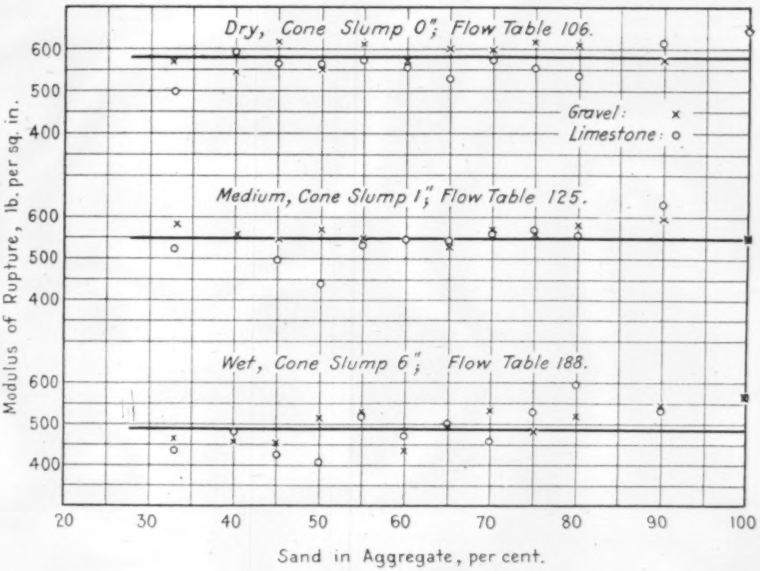

FIG. 6.—Showing Effect on Strength of Variations in Sand Content. Transverse Test, Gravel and Limestone, from Table II.

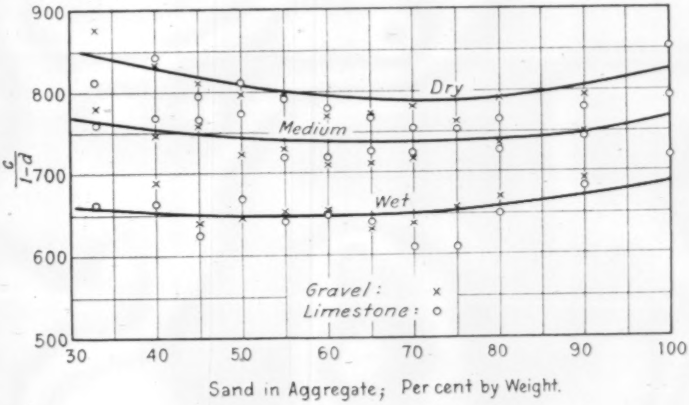

FIG. 7.—Cement Voids—Sand Curve.

The theory upon which the proportioning is based (R. W. Crum, "Proportioning of Pit-Run Gravel for Concrete," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II, p. 458 (1919), assumes that for equivalent mixtures the ratio cement : voids will be approximately a constant. Considering the lack of extreme delicacy in these measurements, the assumption is substantially verified, especially in the case of the medium consistency.

material is ordered. Further, an unscreened gravel aggregate must be used from stock piles containing at least 1000 cubic yards in order to insure uniformity of proportions of the fine and coarse aggregate, and to prevent undue segregation of the fine and coarse particles.

TABLE IV.—PROPORTIONS FOR SCREENED AND UNSCREENED GRAVEL AGGREGATE.

Sand in Aggregate, per cent by weight.	Proportion by Weight, Cement to Gravel.		Approximate Quantity of Cement, bbl. per cu. yd.
	Pit-run Gravel.	Screened Gravel.	
33	1 : 5.18	1 : 1.71 : 3.47	1.6
34 to 40	1 : 4.84	1 : 1.93 : 2.91	1.67
41 to 45	1 : 4.59	1 : 2.06 : 2.53	1.74
46 to 50	1 : 4.34	1 : 2.17 : 2.17	1.80
51 to 55	1 : 4.10	1 : 2.25 : 1.85	1.87
56 to 60	1 : 3.84	1 : 2.30 : 1.54	1.95
61 to 65	1 : 3.60	1 : 2.34 : 1.26	2.04
66 to 70	1 : 3.35	1 : 2.34 : 1.01	2.15
71 to 75	1 : 3.10	1 : 2.33 : 0.77	2.26
76 to 80	1 : 2.86	1 : 2.29 : 0.57	2.39
81 to 85	1 : 2.61	1 : 2.22 : 0.39	2.53
86 to 90	1 : 2.36	1 : 2.12 : 0.24	2.71
91 to 95	1 : 2.12	1 : 2.01 : 0.11	2.89
96 to 100	1 : 1.87	1 : 1.87	3.13

RELATIONS BETWEEN VOIDS AND PLASTICITY OF CEMENT MORTARS AT DIFFERENT RELATIVE WATER CONTENTS.

By Frank E. Richart[1] and Edward E. Bauer.[2]

Voids and Cement Content of Mortars.

In the study of methods of proportioning of concrete and of the laws of action of concrete mixtures, attention has naturally been directed to the properties of cement mortars, both with regard to the quality of the separate constituent materials and to the behavior of the mortar as related to that of concrete. The investigations of Feret[3] have often been quoted as a classical contribution to the literature concerning cement mortars, and served to define many natural laws governing such mixtures. Numerous subsequent tests have been made, particularly in the work of developing specifications for cement and fine aggregates. The subject has been attacked from various angles and a great amount of information has been accumulated. In 1921, attention was redirected to the principles set forth by Feret through a paper by A. N. Talbot[4] in which the density and strength of concrete mixtures were studied by means of analysis and tests of the properties of mortars. The paper gave quantitative information on the properties of various mortars, emphasized the relation between cement content, voids, and strength, and described a rapid laboratory method of determining the voids in any mortar mixture made with a given sand. Certain uses of this mortar-voids test form the basis of the present paper.

Briefly, the following principle may be stated regarding the voids in cement mortar: (1) when a mixture of dry sand and cement is gaged with increasing amounts of water there occurs at first a swelling or bulking of the mass much as is produced in sand alone when dampened; (2) this is followed by a gradual decrease in the volume as the mixture develops cohesive properties until a point of minimum volume is reached, where the mortar begins to become plastic; and (3), with more water an increase in the volume is caused by the mechanical separation of the particles, or dilution of the mixture, by the additional water. Since the absolute volume of the solids remains constant, the variation in the volume of the mass produces a corresponding variation in the voids, as may be noted by a study of Fig. 1. A mortar composed of two parts of Attica sand to one part of cement by absolute volume has been used. The distance between curves indicates the relative space occupied by the cement, sand, and voids (water and air) with the different quantities of water used. As will be noted later, a certain definite amount of water is required to produce minimum voids and it appears that this amount of water may be used as a standard in determining the proper amount of mixing water for mortars used in test specimens.

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[2] Instructor in Highway Engineering, University of Illinois.

[3] R. Feret, *Bulletin* de la Société d'Encouragement pour l'Industrie Nationale, 1897. Also *Annales des Ponts et Chaussées*, 1892.

[4] A. N. Talbot, "A Proposed Method of Estimating the Density and Strength of Concrete and of Proportioning the Materials by the Experimental and Analytical Consideration of the Voids in Mortar and Concrete," *Proceedings*, Am. Soc. Test. Mats., Vol. 21, p. 940 (1921).

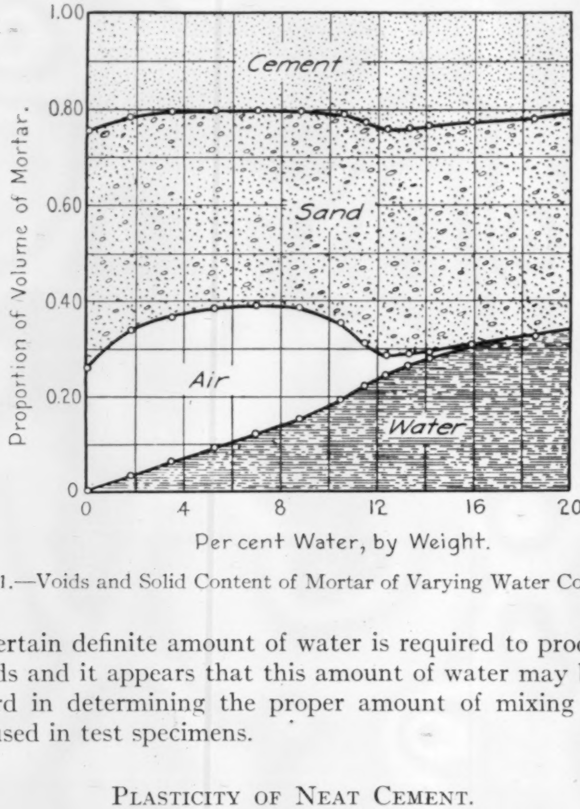

FIG. 1.—Voids and Solid Content of Mortar of Varying Water Content.

PLASTICITY OF NEAT CEMENT.

The typical mortar-voids relation has been found with neat cement mixtures as well as in sand mortars. The point of minimum voids is well defined and it has been found possible to duplicate its determination satisfactorily in repeated tests. The feature of particular interest, however, is that the water producing minimum voids (which has been termed the *basic water content*) appears to coincide quite closely with the water required by the standard Vicat test for normal plasticity. This is not especially surprising; the decided compactness of neat cement at normal plasticity is well known, also that this is the plasticity that produces approximately the maximum strength. However, the quantitative relation between the minimum voids and normal plasticity throws new light on the subject.

The mortar-voids and Vicat tests have been made on seven brands of portland cement in order to study the agreement of the two methods. The results are shown in Table I, and in the curves of Fig. 2, where only the portion of the curves near the point of minimum voids are plotted. Curves are shown both for neat mixes and for standard 1 : 3 Ottawa sand mortars. It is noticeable that the Hoosier cement, which is finely ground (11.5 per cent retained on No. 200 sieve) shows high voids and requires the highest percentage of water to produce the condition of minimum voids.

TABLE I.—DATA OF VICAT AND MINIMUM VOIDS TESTS.

Brand of Cement.	Neat.			1 : 3 Ottawa Mortar.		
	Normal Plasticity by Vicat Test, Water, per cent.	Minimum Voids Test.		Water Required by Specifications, per cent.	Minimum Voids Test.	
		Water, per cent.	Voids in Mixture.		Water, per cent.	Voids in Mortar.
Hoosier	26.6	26.0	0.476	10.9	10.5	0.289
Medusa	25.0	24.5	0.446	10.7	9.5	0.280
Universal	24.5	23.0	0.450	10.6	9.5	0.300
Atlas	24.3	24.0	0.441	10.6	9.0	0.286
Marquette	23.9	23.5	0.440	10.5	9.5	0.291
Owl	22.8	23.0	0.432	10.3	9.2	0.294
Lehigh	22.6	22.5	0.430	10.3	9.5	0.293

The method of making voids determination is simple, requiring only an accurate balance, a glass or metal mold or container, a mixing pan, trowel and tamping rod. A burette is also convenient for measuring the mixing water. A 2 by 4-in. cylinder mold with a tight bottom makes a desirable form of container. With this size of mold, 600 g. of cement is weighed out, accurately to 1 g., and is mixed in the ordinary way with the gaging water which is measured with a similar degree of accuracy. When the batch is thoroughly mixed, it is placed in the container and tamped in the manner followed in making test specimens. With dry mixtures it has been found desirable to use a flat-ended wooden tamper, $\frac{3}{4}$ in. square, since a pointed rod leaves cavities in the mixture instead of compacting it. The mold is filled, struck off neatly and weighed, the operation being repeated as a check. From the weights and the specific gravity of the cement, the voids are easily found. About the same number of trials are needed to determine the desired plasticity as are required for the Vicat test. While the voids test is not offered as a substitute for the Vicat test, it has the appearance of a reasonably consistent method of determining the normal plasticity of cements; this agreement for neat mixtures may throw light upon the suitability of the voids test as a measure of the normal plasticity or workability of mortar and concrete.

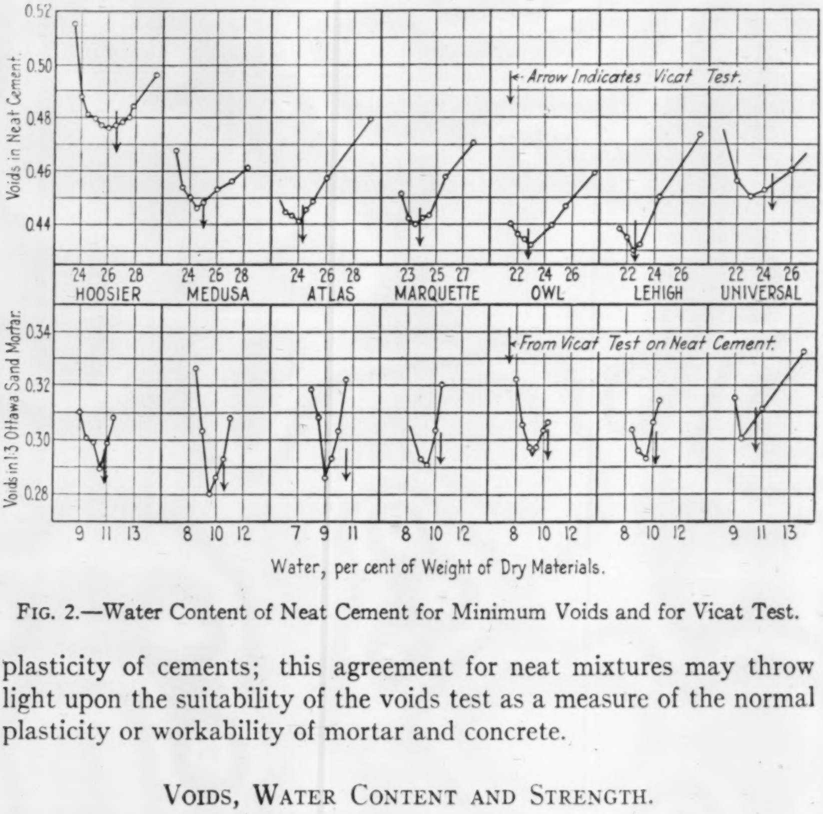

FIG. 2.—Water Content of Neat Cement for Minimum Voids and for Vicat Test.

VOIDS, WATER CONTENT AND STRENGTH.

The curves of Fig. 1 showed the variation of voids and solid contents of a mortar mixture when the amount of mixing water was increased. By making similar determinations for several mortars of varying degrees of richness, using the same sand and cement, the behavior of any ordinary mortar mixture may be estimated. Fig. 3 shows results of mortar-voids tests made on Ottawa sand with values of $\frac{a}{c}$ equal to 0, 1, 2, 3, 3.5, 4 and 5, the following notation being used:

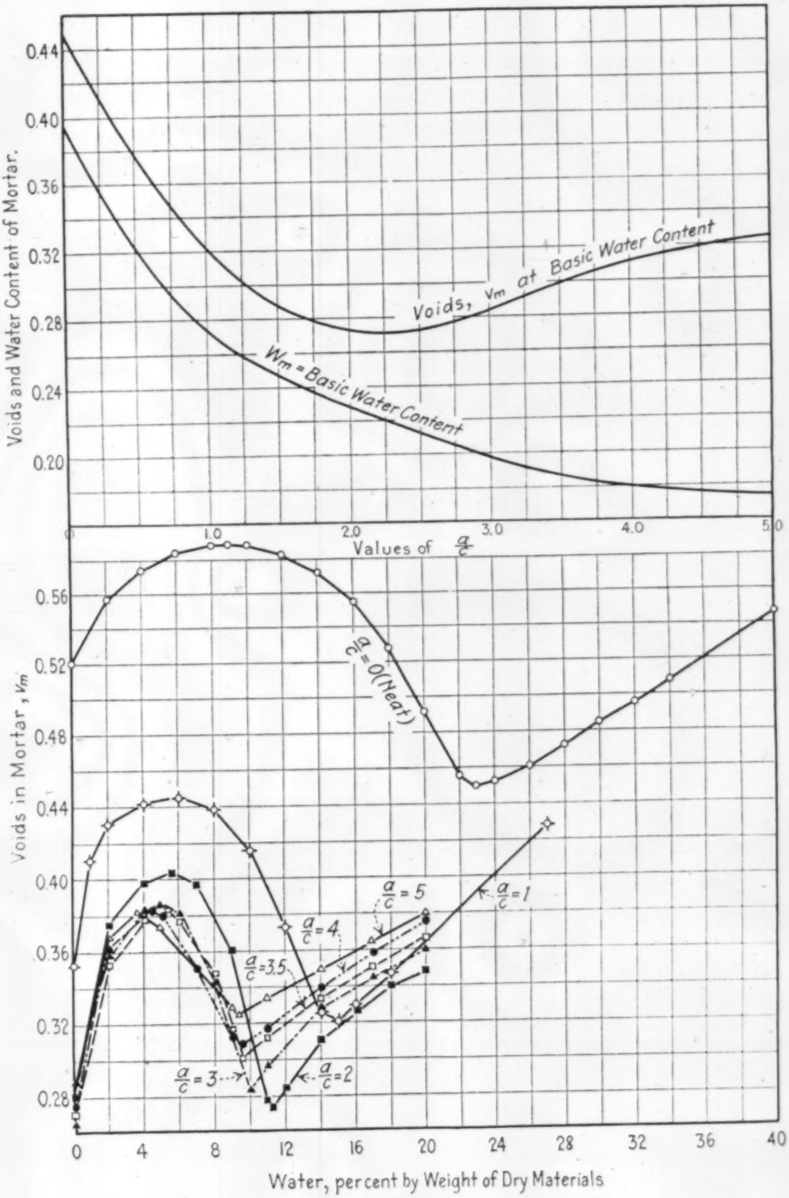

FIG. 3.—Mortar-voids Curves for Ottawa Sand.

a equals absolute volume of fine aggregate, c equals absolute volume of cement, v_m equals voids in mortar and w_m equals volume of water in a unit volume of mortar. It is seen that the ratio $\frac{a}{c}$ is roughly one-sixth greater than the ratio by weight of ordinary sand to cement, and 20 to 40 per cent greater than the ratio by bulk volume of sand to cement. The minimum voids and basic water content have been used to plot characteristic curves for v_m and w_m for the materials used, as shown in Fig. 3. Similar curves could be drawn for other relative water contents.

As a further study of the relations between voids, water content and strength, a small series of tension and compression tests was made, using one brand of cement and four grades of sand. The Attica sand was a coarse well-graded, washed sand, the Covington sand was a finer plastering sand, the Jewett sand was a very fine bank sand and the fourth sand was the standard Ottawa sand used in cement testing. Universal portland cement was used. Properties of the aggregates are given in Table II. Six briquettes of a kind were tested at 7 days, the same number at 28 days, and five 2 by 4-in. cylinders of a kind were tested in compression at 28 days. A series of compression tests made in 1919 is also included for comparison with these tests. The Universal cement used in 1919 was naturally of a different lot from that used in the 1922 tests; each value represents the average of tests of four 6 by 12-in. cylinders of a kind. All compression specimens remained in the molds for one day after molding, then were placed in a moist room in which the air was kept moist by humidifying sprays, and were removed one day before testing. Briquettes were left in the molds one day, then were stored in water until just before testing. The voids and water content of all mixes were recorded and an attempt

TABLE II.—DATA OF FINE AGGREGATES.

No.	Description.	Specific Gravity.	Weight, per cu. ft., lb.	Surface Modulus.	Fineness Modulus.	Per Cent by Weight Passing each Sieve.					
						100	48	28	14	8	4
0	Standard sand from Ottawa, Ill.	2.65	105	12.6	2.99	0	0	1	100	..	..
24	Well-graded sand from Attica, Ind.	2.67	112	16.6	3.34	4	10	25	51	78	97
28	Plastering sand from Covington, Ind.	2.67	103	23.8	2.28	3	12	58	100	..	..
30	Fine bank sand from Jewett, Ill.	2.63	102	39.8	1.47	7	54	99	100	..	..
3	Sand from Algonquin, Ill.	2.71	117	22.6	2.79	5	19	46	67	84	100
10	Dune sand from Gary, Ind.	2.67	101	51.6	1.00	6	95	100	..	..	..
15	Crushed slag from Lorain, Ohio	2.59	91	17.9	3.70	9	15	24	34	55	93
16	Granulated slag from Buffington, Ind.	2.50	81	22.6	2.69	7	15	37	76	98	99
19	Sand from Janesville, Wis.	2.65	116	21.4	2.84	1	14	57	73	82	90

TABLE III.—DATA OF TESTS OF MORTARS.

Water.		Cement, c	Water-Cement Ratio, by Volume.	Voids in Mortar, v_m	$\frac{c}{v_m + c}$	Slump, 2 × 4-in. Cylinder, in.	Strength, lb. per sq. in.			Ratio, $\frac{\text{Compression}}{\text{Tension}}$, 28 days.
Per Cent by Weight.	w_m						Tension.		Compression.	
							7 days.	28 days.	28 days.	
ATTICA SAND, $\frac{a}{c} = 3.5$										
9	0.185	0.165	0.544	0.257	0.392	0	281	399	2600	6.5
10	0.211	0.170	0.602	0.235	0.420	$\frac{1}{16}$	309	473	3910	8.3
11	0.230	0.167	0.669	0.247	0.404	$\frac{1}{8}$	291	488	4220	9.0
12	0.246	0.164	0.728	0.262	0.385	$\frac{3}{8}$	275	433	3990	9.2
13	0.262	0.161	0.790	0.275	0.370	$\frac{13}{16}$	244	438	3420	7.8
15	0.295	0.158	0.907	0.296	0.348	2	219	404	2520	6.3
ATTICA SAND, $\frac{a}{c} = 2.5$										
9	0.172	0.195	0.428	0.316	0.382	0	229	332	2100	6.3
10	0.203	0.207	0.476	0.274	0.430	0	338	450	3640	8.1
11	0.233	0.216	0.524	0.244	0.470	$\frac{1}{8}$	423	526	5760	11.0
12	0.251	0.214	0.570	0.251	0.460	$\frac{3}{16}$	429	624	5980	9.6
13	0.266	0.209	0.617	0.268	0.439	$\frac{5}{8}$	418	570	5030	8.8
15	0.297	0.202	0.714	0.293	0.408	$1\frac{7}{8}$	362	535	4680	8.7
COVINGTON SAND, $\frac{a}{c} = 3.5$										
9	0.166	0.149	0.540	0.329	0.312	0	202	252	1280	5.1
10	0.190	0.152	0.601	0.312	0.328	0	207	326	1510	4.6
11	0.218	0.156	0.661	0.294	0.347	0	284	380	2180	5.7
12	0.240	0.160	0.721	0.277	0.368	$\frac{1}{16}$	264	403	3060	7.6
13	0.260	0.160	0.782	0.277	0.369	$\frac{1}{16}$	259	404	2860	7.1
14	0.273	0.156	0.842	0.294	0.347	$\frac{1}{8}$	238	373	2950	7.9
16	0.301	0.151	0 963	0.321	0.320	$1\frac{1}{4}$	208	367	2890	7.9
COVINGTON SAND, $\frac{a}{c} = 2.5$										
10	0.185	0.189	0.471	0.335	0.362	0	247	292	1650	5.7
11	0.216	0.201	0.520	0.297	0.404	0	322	358	2890	8.1
12	0.237	0.202	0.566	0.293	0.408	0	356	483	3510	7.3
13	0.259	0.204	0.618	0.285	0.418	$\frac{1}{16}$	375	518	4520	8.7
14	0.278	0.203	0.661	0.288	0.413	$\frac{3}{16}$	334	507	4740	9.3
15	0.292	0.198	0.709	0.305	0.394	$\frac{9}{16}$	328	498	4700	9.5
17	0.319	0.192	0.804	0.329	0.368	$1\frac{1}{8}$	265	445	4240	9.5
JEWETT SAND, $\frac{a}{c} = 3.5$										
10	0.182	0.149	0.592	0.332	0.310	0	145	179	1200	6.7
11	0.198	0.147	0.653	0.339	0.305	0	165	230	1330	5 8
12	0.215	0.146	0.690	0.342	0.300	0	168	218	1540	7.1
13	0.242	0.151	0.777	0.318	0.322	0	164	251	1910	7.6
13.5	0.249	0.151	0.802	0.322	0.319	0	170	252	1760	7.0
14	0.259	0.148	0.850	0.320	0.316	0	167	256	1950	7.6
16	0.290	0.150	0.938	0.333	0.307	$\frac{3}{16}$	149	247	1860	7.5

TABLE III.—DATA OF TESTS OF MORTARS.—*Continued.*

Water.		Cement, c	Water-Cement Ratio, by Volume.	Voids in Mortar, v_m	$\frac{c}{v_m + c}$	Slump, 2 × 4-in. Cylinder, in.	Strength, lb. per sq. in.			Ratio, $\frac{\text{Compression}}{\text{Tension}}$.
							Tension.		Compression.	
Per Cent by Weight.	w_m						7 days	28 days.	28 days.	28 days.
JEWETT SAND, $\frac{a}{c} = 2.5$										
11	0.195	0.184	0.515	0.355	0.341	0	197	246	960	3.9
12	0.213	0.183	0.564	0.357	0.339	0	233	312	1230	3.9
13	0.236	0.188	0.607	0.340	0.356	0	258	326	1950	6.0
13.5	0.248	0.193	0.622	0.330	0.369	0	247	346	2300	6.6
14	0.260	0.192	0.656	0.326	0.371	0	247	360	2130	5.9
15	0.278	0.188	0.719	0.328	0.365	$\frac{1}{8}$	236	363	2370	6.5
17	0.308	0.191	0.782	0.344	0.357	$\frac{1}{4}$	217	336	2490	7.7
OTTAWA SAND, $\frac{a}{c} = 3.5$										
9	0.176	0.157	0.544	0.292	0.350	0	195	257	1935	7.5
9.5	0.190	0.160	0.578	0.278	0.366	0	203	296	2480	8.4
10	0.200	0.160	0.607	0.279	0.365	0	214	311	2634	8.5
11	0.220	0.160	0.667	0.280	0.364	0	188	281	3320	11.8
12	0.236	0.158	0.724	0.287	0.355	$\frac{1}{16}$	180	277	2935	10.6
13	0.251	0.154	0.792	0.305	0.336	$\frac{1}{8}$	171	264	2865	10.8
15	0.279	0.149	0.908	0.327	0.313	$\frac{1}{4}$	158	271	2575	9.5
OTTAWA SAND, $\frac{a}{c} = 2.5$										
9	0.173	0.197	0.427	0.310	0.389	0	225	251	2080	8.3
10	0.198	0.203	0.476	0.289	0.413	0	260	369	2820	7.9
10.5	0.214	0.209	0.495	0.267	0.425	0	292	416	4295	10.3
11	0.229	0.213	0.520	0.254	0.456	$\frac{1}{16}$	303	415	4542	10.9
12	0.248	0.210	0.568	0.264	0.443	$\frac{1}{8}$	282	437	5300	12.1
13	0.258	0.202	0.622	0.288	0.414	$\frac{3}{8}$	240	363	4615	12.7
15	0.290	0.198	0.709	0.308	0.393	$\frac{3}{8}$	219	358	4895	13.7
NEAT UNIVERSAL CEMENT, 1922 TESTS.										
20	0.347	0.556	0.303	0.444	0.556	0	423	474	5200	11.0
21	0.378	0.578	0.318	0.422	0.578	0	440	543	9395	17.3
22	0.394	0.575	0.333	0.425	0.575	0	638	687	9290	13.5
23	0.405	0.564	0.350	0.436	0.584	0	621	710	9560	13.5
24	0.420	0.561	0.363	0.439	0.561	$\frac{3}{16}$	554	559	9940	17.8
25	0.432	0.555	0.378	0.445	0.555	$\frac{5}{16}$	543	712	10090	15.3
26	0.442	0.545	0.393	0.455	0.545	$\frac{1}{2}$	553	637	9590	15.0
28	0.459	0.526	0.423	0.474	0.526	$\frac{9}{16}$	513	677	7645	14.3
30	0.481	0.515	0.454	0.485	0.515	$1\frac{9}{16}$	443	547	8810	16.1
35	0.520	0.477	0.529	0.523	0.477	$2\frac{3}{4}$	424	525	5935	11.3
40	0.555	0.444	0.607	0.556	0.444	$3\frac{1}{4}$	331	489	6375	13.0

TABLE III.—DATA OF TESTS OF MORTARS.—*Continued.*

Water.		Cement,	Water-Cement Ratio, by Volume.	Voids in Mortar, v_m	$\frac{c}{v_m + c}$	Slump, 2 × 4-in. Cylinder, in.	Strength, lb. per sq. in.			Ratio, Compression / Tension.
Per Cent by Weight.	w_m						Tension. 7 days.	Tension. 28 days.	Compression. 28 days.	28 days.
					NEAT UNIVERSAL CEMENT, 1919 TESTS.					
19	0.308	0.523	0.286	0.477	0.523	....	...	275	1850	6.7
21	0.371	0.570	0.316	0.430	0.570	....	...	666	8390	12.6
23	0.400	0.561	0.346	0.439	0.561	....	...	697	8245	11.8
25	0.423	0.546	0.376	0.454	0.546	....	...	678	7865	11.6
27	0.444	0.530	0.407	0.470	0.530	....	...	661	7110	10.8
29	0.464	0.516	0.436	0.484	0.516	....	...	652	6505	10.0
31	0.484	0.503	0.467	0.497	0.503	....	...	576	5995	10.4
33	0.500	0.501	0.481	0.499	0.501	....	...	547	5480	10.0
35	0.518	0.477	0.527	0.523	0.477	....	...	541	5025	9.3
37	0.533	0.464	0.557	0.536	0.464	....	...	522	4075	7.8
39	0.547	0.455	0.583	0.545	0.455	....	...	436	3600	8.3
41	0.557	0.438	0.617	0.562	0.438	....	...	426	3570	8.4
43	0.567	0.425	0.647	0.575	0.425	....	...	414	3385	8.2
45	0.581	0.416	0.678	0.584	0.416	....	...	376	3195	8.5
47	0.594	0.408	0.707	0.592	0.408	....	...	392	2930	9.7
50	0.609	0.390	0.758	0.610	0.390	....	...	365	2015	5.5

was made to measure the workability of the mortar in the 1922 tests by means of a "slump" test, made on a 2 by 4-in. cylinder.

The principal results of the tests are given in Table III. It will be noted that the amount of water is tabulated in two ways: in per cent of the weight of the dry materials and as w_m, the volume of water per unit volume of mortar. The cement is given as c, the absolute volume of cement per unit volume of mortar. The remainder of the table is self-explanatory.

A comparison of the water required for maximum strength and for minimum voids as plotted in Figs. 4 and 5 shows, in general, close agreement; in some cases the maximum strength was obtained with 105 to 110 per cent of the basic water content. The relation between strength and voids of neat cements, particularly in the 1919 tests, appears quite definite. The compressive strength of the Jewett sand mortar is the only noticeable deviation from the general rule. This sand is of course too fine for use in mortar or concrete, but was used in the tests as an example of an extreme of size and gradation of aggregate. In this mortar the point of minimum voids was not well defined, there was little variation in tensile strength with different water contents, and apparently more information would have been secured if

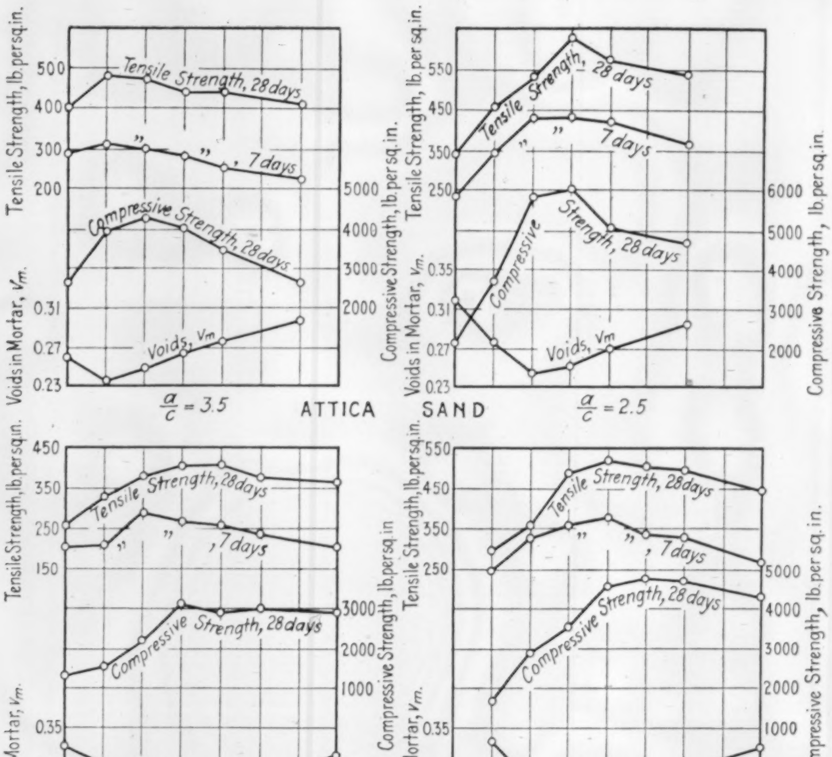

FIG. 4.—Strength, Voids, and Water Content of Mortars.

still wetter mixtures had been used. Unfortunately, in making the compression specimens, a metal tamping rod was used which was

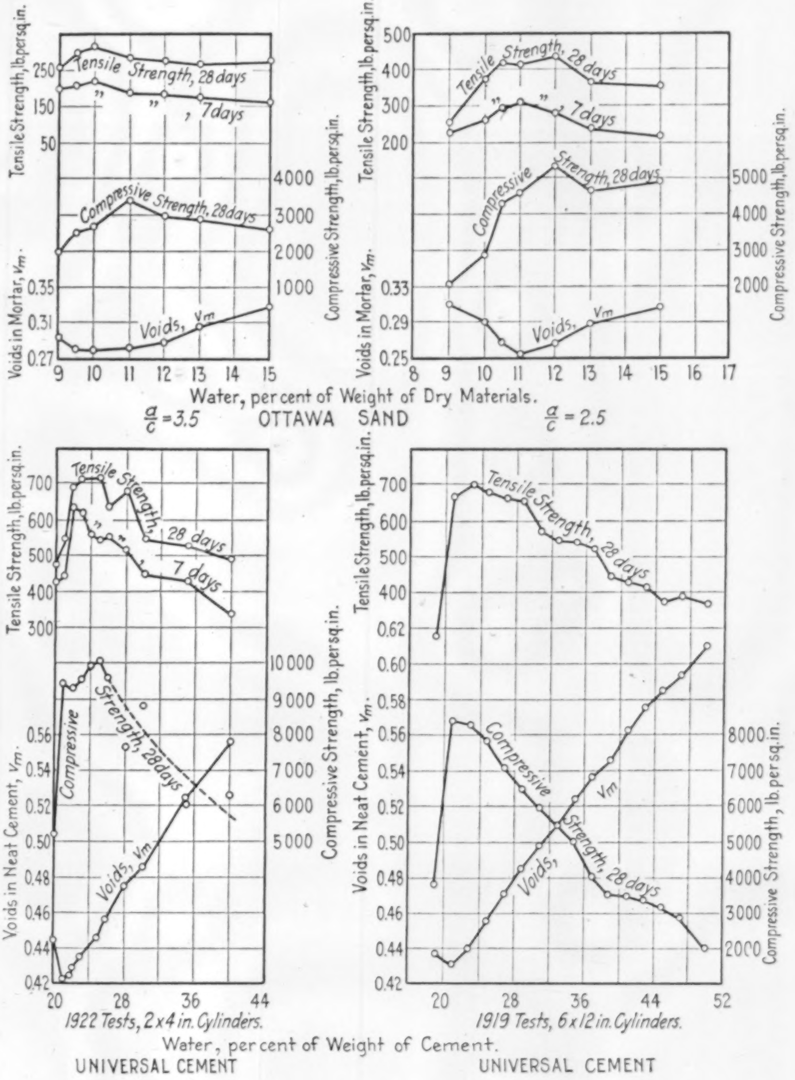

FIG. 5.—Strength, Voids, and Water Content of Mortar and Neat Cement.

considerably heavier than the wooden tamper used in other voids determinations, and consequently the minimum voids found in these specimens are somewhat lower than have been found in other trials, although the basic water content is not affected.

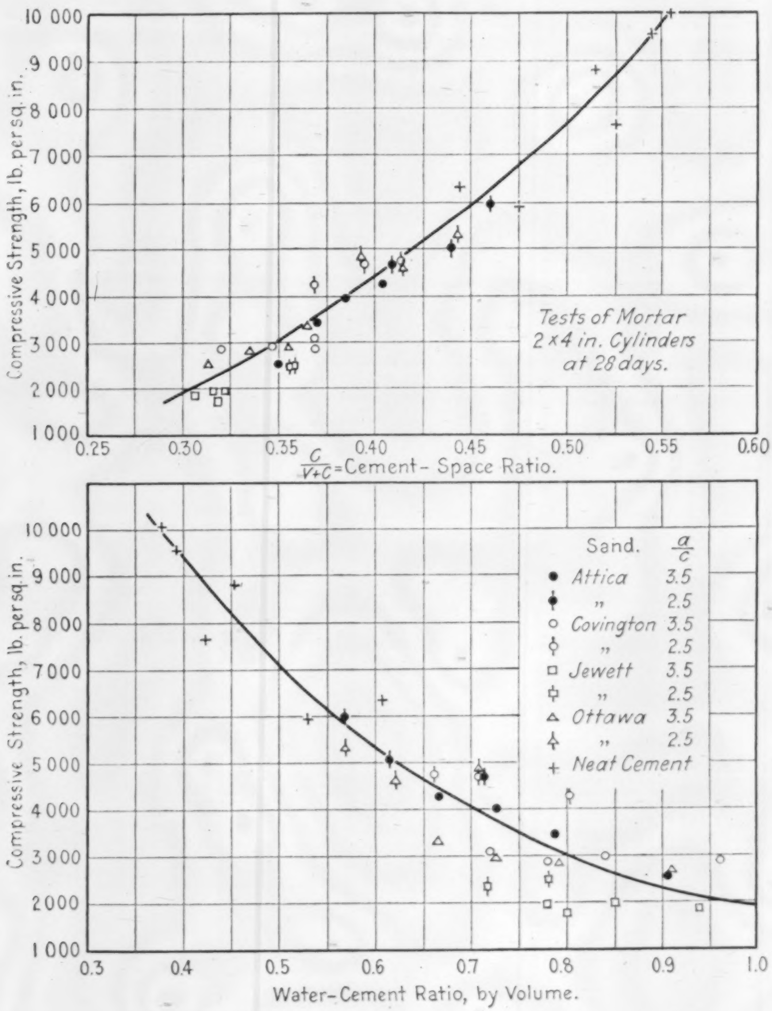

FIG. 6.—Strength, Cement-space Ratio and Water-cement Ratio of Mortars.

It should be kept in mind that the object of the tests was mainly to study the strength of mortars near the basic water content; the mortars having less than basic water content are not easily workable mixes and cannot be expected to follow at all closely the laws that govern the strength of workable mixtures. Omitting the results, therefore, of the mortars containing less than basic water content, the curves of Fig. 6 have been plotted to show the relation of strength to cement-space ratio and to water-cement ratio. The term cement-space ratio is used to denote the quantity $\frac{c}{v+c}$, or the ratio of the absolute volume of the cement content to the space occupied by the cement paste (cement, water and air); the water-cement ratio is the ratio of the volume of water to the bulk volume of dry cement, as it has been commonly used. There appears to be a well-defined relation between the compressive strength and the cement-space ratio in Fig. 6, while the effect of water-cement ratio upon the strength is somewhat less pronounced. The curves of Fig. 6 are similar in shape to curves that have been derived from other tests; in using numerical values, however, it must be remembered that the strength is affected by the kind and quality of the cement as well as by the variables shown in the figure.

WATER REQUIREMENTS FOR MORTAR TESTS.

Tension or compression tests of mortar are frequently prescribed in specifications for fine aggregate, but in most instances the required water content is rather indefinite. One well-known specification requires that a 1 : 3 mortar made with the given fine aggregate shall produce a strength "not less than that of 1 : 3 standard Ottawa sand mortar *of the same plasticity* made with the same cement." A standard European specification requires that the mortar used in test specimens shall be of such consistency that "there is no surplus of moisture when it is gently beaten with a trowel." It is evident that if the proper consistency is left to the judgment of the operator a true comparison of the quality of sands is less likely to be made. The consistency of mortars made with fine sands is especially hard to judge. The use of some form of workability test may not afford a proper criterion as to whether the latent possibilities of strength of the mortar are being developed. From tests that have been made it seems possible that the use of the basic water content, or some proportion thereof, might be used as a standard water content for comparative tests of the strength of mortar. For a single mortar mixture, the basic water content may be determined in a few minutes, and values may be obtained in a few hours for all probable mortar mixes using the given sand.

There are in use several formulas for determining the water to produce mortar of standard or normal plasticity. Among these is Feret's[1] formula:

$$w = \frac{2p}{3 + 3n} + k \qquad \text{(1)}$$

where w is the water expressed in per cent of the weight of cement and aggregate, p is the water required for normal plasticity of neat cement expressed in per cent of the weight of cement, n is the ratio of aggregate to cement by weight, and k is a constant.

Another equation, based upon the results of mortar tests, has been developed by Taylor.[2] Using the notation of Eq. 1, it is

$$w = \frac{3p + Sn + 1}{4(n + 1)} \qquad \text{(2)}$$

where S is a constant depending upon the sand.

It is of interest to note how these formulas compare when used with standard Ottawa sand mortar. Eq. 1 has evidently been used as the basis of the values specified for 1 : 3 Ottawa sand mortar in the Standard Specifications for Portland Cement.[3] A value of k of 6.5 is used, although in older specifications the value used was 5.5, giving a drier mixture. For Eq. 2, a value of S is given as 25 for Ottawa sand. For a comparison with the results from Eqs. 1 and 2, a curve of basic water content for Ottawa sand has been plotted in Fig. 7. The value of p for the cement used was 24 per cent. For the 1 : 3 and 1 : 4 mixes, the values from Eq. 1 compare well with the basic water content; the latter agrees more closely at a 1 : 2 mix with the value from Eq. 2; at mixtures approaching neat cement, both equations contain obvious errors since they do not reduce to the value p for the neat cement mixture.

Fig. 8 shows curves of basic water content for a number of fine aggregates. A description and certain properties of the aggregates are given in Table II. These curves show in general that the finer materials and rich mixtures require high water contents, well-graded sands and leaner mixtures the lower amounts, while a few materials of peculiar grading require more water in a lean mix than in a rich one. Since each sand is seen to have individual characteristics that affect the water requirement, formulas of the form ot Eqs. 1 and 2 may hardly be expected to satisfy the conditions of a variety of sands and the mortar-voids test appears to be a more satisfactory method of determining a standard amount of gaging water.

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[1] "Commission des Methodes d'Essai des Materiaux," Vol. IV, 1895.

[2] "Practical Cement Testing," by W. Purves Taylor, p. 110.

[3] Standard Specifications and Tests for Portland Cement (C 9 – 21) of the American Society for Testing Materials, 1921 Book of A.S.T.M. Standards.

PROPORTIONS OF MORTAR FOR TESTS.

It has been mentioned that a 1 : 3 mortar, by weight, is generally specified for tension or compression tests. For ordinary sands this produces a ratio $\frac{a}{c}$ of about 3.5. Except when very well-graded sand is used, such a mortar does not contain sufficient cement paste to envelope fully the sand particles, just as a concrete mixture may contain too great a proportion of coarse aggregate to produce the best results. Furthermore, a comparative test of sands used in 1 : 3 mortar does not indicate their relative qualities when used in concrete having a richer mortar content. For example, the data of Table III show that the relative maximum strengths of mortar made with Attica, Covington and Jewett sands as compared with Ottawa sand

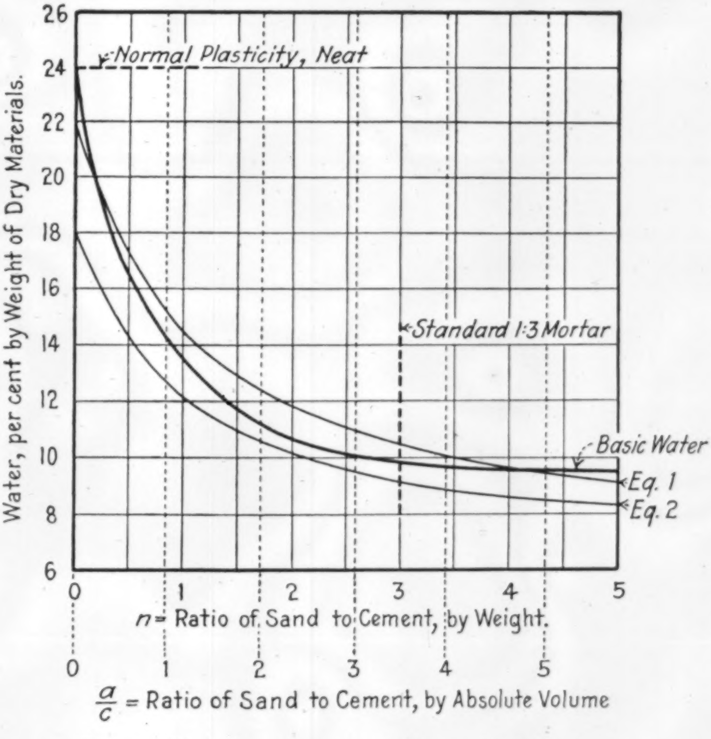

FIG. 7.—Water Requirements of Ottawa Sand Mortars.

mortar are 1.27, 0.92, and 0.59, respectively, with $\frac{a}{c}$ equal to 3.5; but are 1.12, 0.89, and 0.47, respectively, with $\frac{a}{c}$ equal to 2.5. Mixtures ranging from 1 : 2 : 4 to 1 : 1 : 2 probably represent the bulk of the concrete in present road and building construction. It would appear logical therefore to use a richer mortar, say 1 : 2, for comparative tests of sands. This corresponds roughly to a value of $\frac{a}{c}$ of 2.5; however, the 1 : 2 proportion by weight may be simpler to apply in the performance of tests.

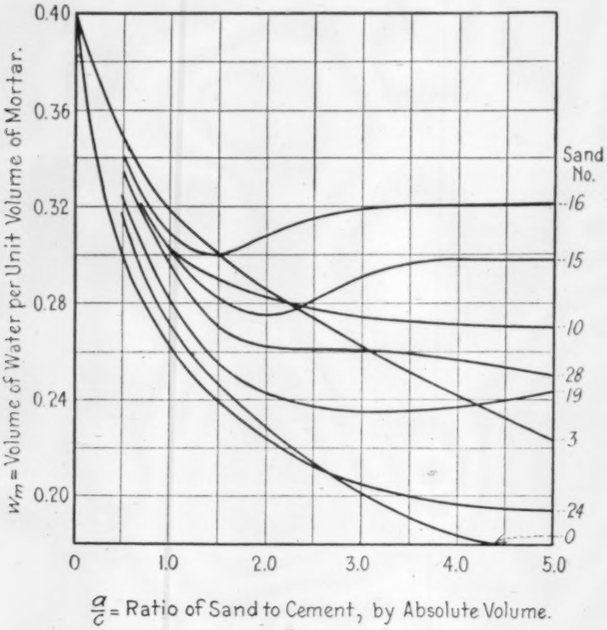

FIG. 8.—Characteristic Curves of Basic Water Content for Several Sands.

WORKABILITY OF MORTARS.

It seems fortunate that the mortar of basic water content, which will produce the full potential strength of the mixture, is very close to the condition termed normal consistency or normal plasticity. From the slump of the 2 by 4-in. cylinders previously noted, it appears that at basic water content the mortar specimen was just beginning to change shape under its own weight. To study this action further mortar mixtures were made with several sands, and measurements

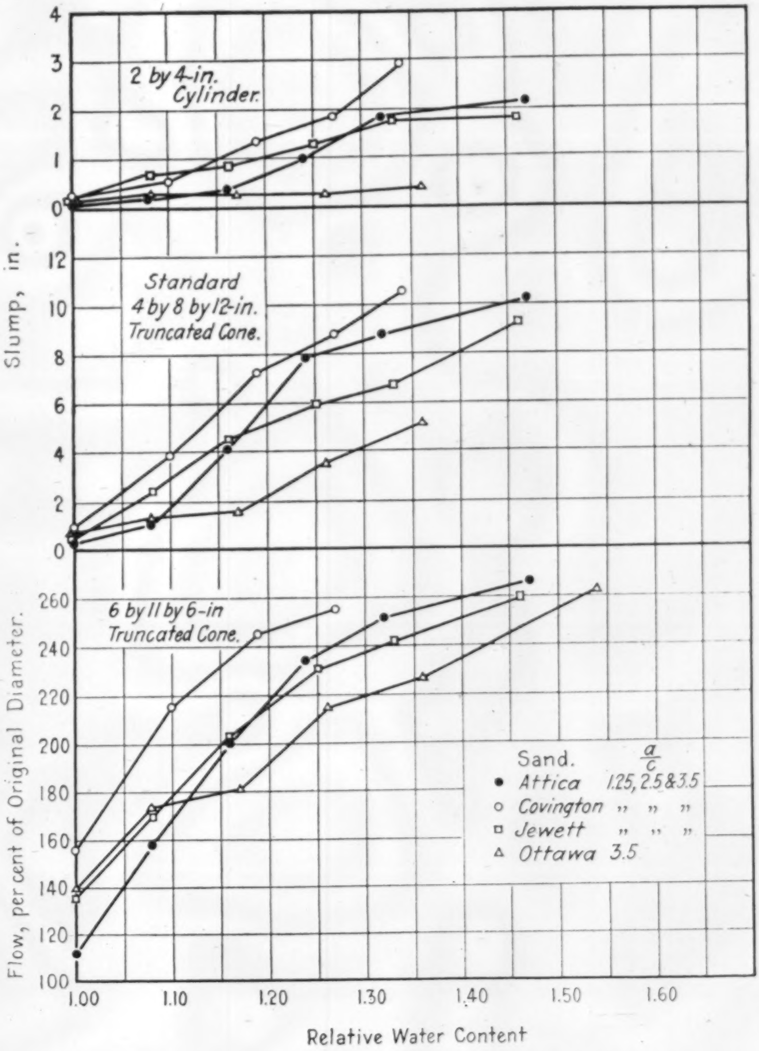

FIG. 9.—Workability and Water Content of Mortars.

were made of voids, water content, flow and slump. The flow test was made according to the A.S.T.M. Tentative Methods of Making

Compression Tests of Concrete (C 39 – 21 T)[1] except that the molded specimen used was slightly larger than the recommended size, being a truncated cone with end diameters of 6 and 11 in. and a height of 6 in. Slump tests were made with the standard 4 by 8 by 12-in. truncated cone and with a 2 by 4-in. cylinder. The results of the workability tests are plotted in Fig. 9. The workability of the different mortars as indicated by slump and flow appears quite variable for the same relative water content. There is a comparatively uniform rate of increase in flow with increase in water content; the variation in slump is less regular. In general, the slump with the small cylinder is a smaller proportion of the original height than the slump with the standard cone. It will be observed that with basic water content the slump with the standard specimen varied from about $\frac{1}{4}$ to 1 in., limits which are frequently specified for concrete of normal consistency. The flow table appears more sensitive to slight differences in the drier mixes, as the flow observed at basic water content varied from 102 to 163 per cent of the original diameter. For further comparison, the

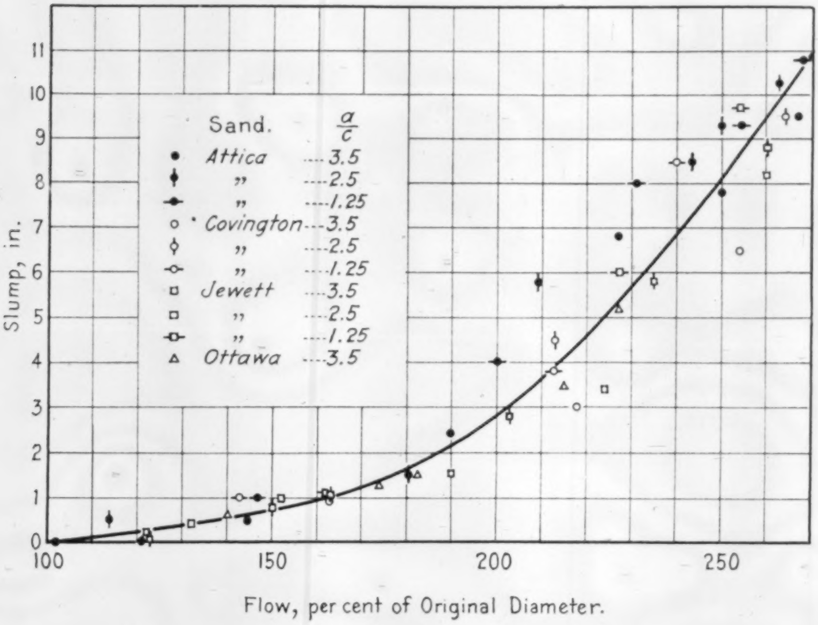

FIG. 10.—Comparison of Flow and Slump Tests.

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[1] *Proceedings*, Am. Soc. Test. Mats., Vol. 21, p. 579 (1921).

flow and slump obtained with the different mortars have been plotted against each other in Fig. 10. In view of the variability shown by these quantities in Fig. 9, the relation between slump and flow seems quite consistent. However, this relation has been found with fairly rich mortar mixes; if these same mortars had been mixed with coarse aggregate, different results would probably have been obtained.

COMMENTS.

The mortar-voids test applied to neat cement or sand mortars furnishes much information regarding the physical structure of the mixture. The usefulness of such information lies in its bearing upon the make-up of concrete mixtures rather than in the significance of the properties of the mortar itself. As an aid to the testing of cement and fine aggregate, the use of basic water content also appears promising and may throw some light on the question of workability. Further study of the relations between the water content and consistency, the space occupied by the various ingredients of a mixture, and the resulting strength, cannot fail to add considerably to present knowledge of the behavior of mortar and concrete.

Acknowledgment.—The writers are indebted to R. L. Brown, First Assistant in the Engineering Experiment Station, University of Illinois, for assistance in the development and performance of tests, and to A. N. Talbot for helpful advice and criticism in the preparation of this paper.

A METHOD FOR MEASURING SANDS IN AN INUNDATED CONDITION.

BY R. L. BERTIN.[1]

The greatest difficulties encountered in producing a fairly uniform concrete in the field is the bulking and water-retaining properties of the fine aggregate. Under the present method of volumetric measurements, the absolute amounts of sand and water introduced in a batch of concrete are more or less indeterminate, the variation being some function of the varying moisture content of the sand and the corresponding bulking.

A new method evolved for measuring sand in an inundated condition seems to indicate the possibility of much closer and more constant measurements than can be obtained by present methods.

The principle on which this method is based is that if sand containing any percentage of moisture is inundated by dropping it into a vessel containing water, so that the vessel is filled to the top with sand and water, the amount of sand and water therein contained will be nearly constant so long as the sand has a constant void factor.

A device was designed for the purpose of measuring simultaneously predetermined amounts of sand and water, accurately and consistently. This device consists of a container shown in Fig. 1, subdivided vertically in two sections, the upper section, *A*, is used to measure inundated sand, and the lower section, *D*, to measure water. Both sections are made adjustable as to capacity by bolting to the bottom of *A* a combination of rings, *E*, of different heights so that for a concrete mix requiring a given quantity of sand and water the two sections can be so adjusted as to contain the proper amount of sand in *A* and the right amount of water required for a concrete batch, the total amount of water being made up of that amount of water which the sand in *A* will hold, which is practically equal to the voids in the sand, plus the amount of water held in *D*. The bottom, *C*, of section *A* is provided with screened openings as shown in section *AA*, Fig. 1, which permit water to enter into and exit from section *D*, but exclude sand from entering it.

The operation of the device consists, after the capacities of the sections have been adjusted, in filling section *D* and approximately $\frac{1}{3}$ of section *A* with water, then filling section *A* with sand. The container is then emptied into the mixer hopper delivering to the mixer definite quantities of sand and water for each batch.

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[1] Chief Engineer, White Construction Co., Inc., New York City.

In order to determine the constancy of the concrete made with the use of this device, tests were made, the results of which are shown in Fig. 2.

Five one-bag batches of concrete were mixed in a power mixer in the proportions of 1 bag of cement, 1.77 cu. ft. of sand (measured in an inundated condition) and 3.60 cu. ft. of gravel. The numbers to the right of the diagram designate the 5 batches which were tested. Batches Nos. 1100 and 1200 were made with dry sand, Batch No. 1400 was made with damp sand containing approximately 6 per cent of water which for the sand used is the percentage causing maximum bulking and Batches Nos. 1600 and 1700 were made with wet sand containing approximately 14 per cent of water. In every batch

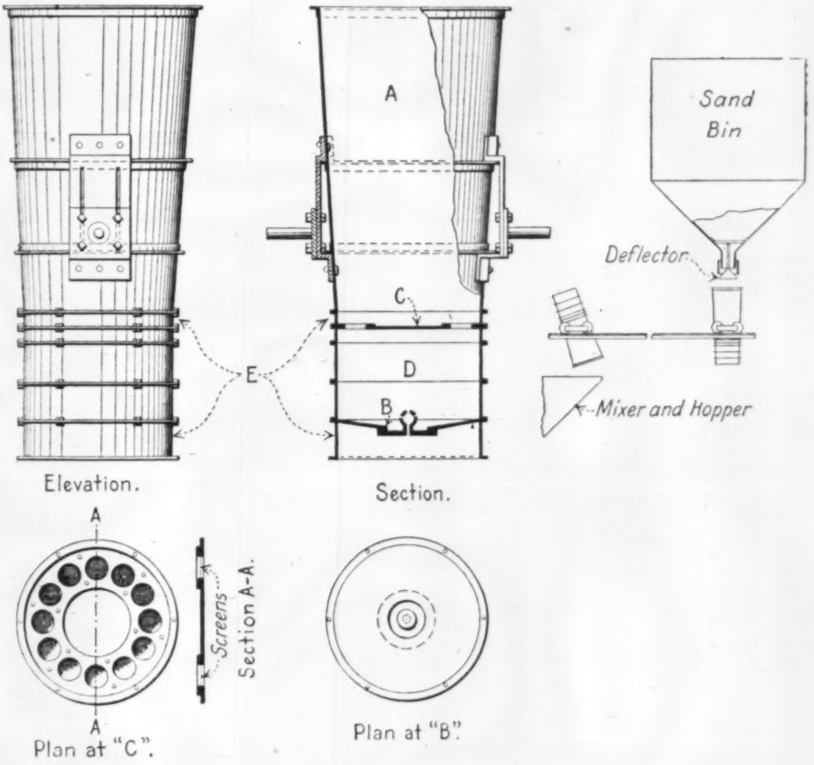

FIG. 1.—Device for Measuring Sand in an Inundated Condition.

the sand in the condition mentioned above was poured in water previously put into the measuring device and the sand so measured together with the water it held, was emptied into the mixer hopper and for all batches 22 lb. of water were added.

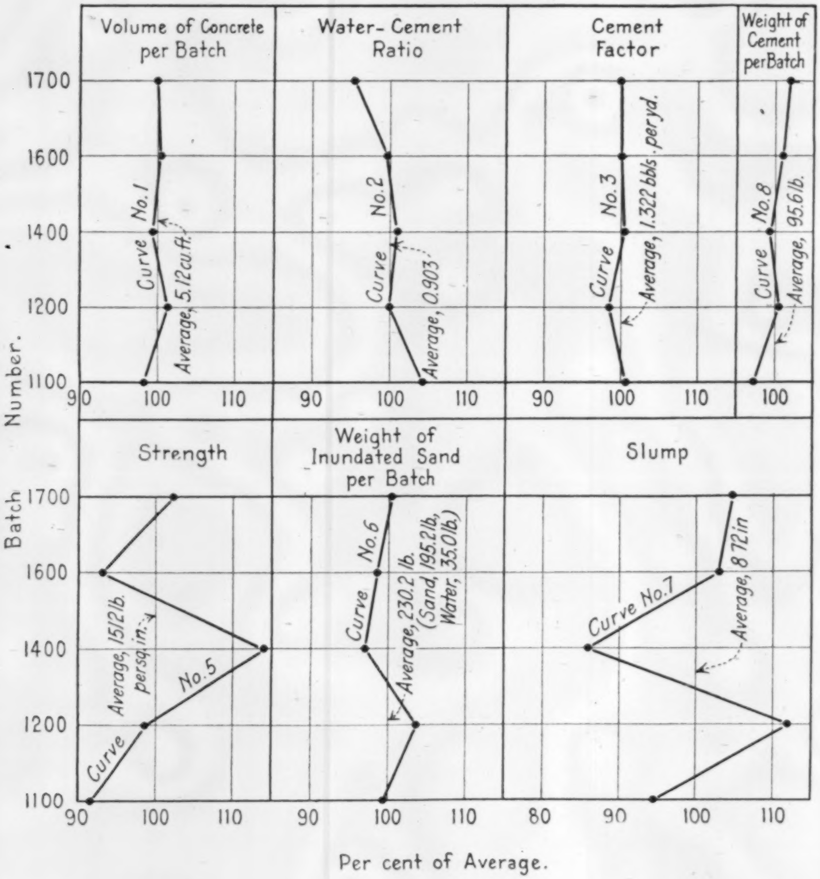

FIG. 2.—Variation from Average of Tests on Sand Measured in Inundated Condition.

From the determinations noted, the volume of concrete per batch, the water-cement ratio, the cement factor, the weight of cement per batch and the weight of inundated sand per batch were computed; slump tests were made (from 6 by 12-in. cylinders), 6 by 12-in. cylinders were cast and tested at 28 days.

The similar determinations for the five batches were averaged and the averages indicated in Fig. 2 as 100 per cent, the actual value being also indicated, curves were plotted showing the amount every one of the batches varied in per cent above or below the average.

Curve No. 1, plotted for the volume of concrete per batch, shows that the amount of concrete produced was practically the same for every batch, notwithstanding the difference in moisture content of the sand in the different batches.

Curve No. 2, plotted for water-cement ratio, indicates very slight variations when consideration is given to the fact that a uniform amount of water was added to every batch in spite of the varying amount of moisture contained in the sand for the different runs. The variations in this curve are due partly to the variations in the weight of the cement contained in the bags used in the different batches as shown by Curve No. 4. It is to be noticed that the weight of cement curve varies inversely as the water-cement ratio curve; had the weight of cement been constant, the water-cement ratio curve would show less deviation from the average.

The cement factor curve indicates very slight variations from the average, which of course follows from Curves Nos. 1 and 4.

Curve No. 5 shows the variations in strength, and Curve No. 7, variations in slumps. While the strength and slump vary to a greater extent than the other factors, the results may be considered fairly constant for such tests.

Curve No. 6 shows the variation in amount of sand and water contained in 1.77 cu. ft. The variations are small and are not sufficiently large to affect materially the volume of concrete per batch as indicated by Curve No. 1.

The results shown in Fig. 2 indicate the possibility of producing, by the use of the device described above, fairly constant concrete, no matter what the condition of the sand is relative to moisture content.

FATIGUE OF CONCRETE.

BY H. F. CLEMMER[1]

Investigations of concrete pavement failures which have occurred during the past few years in the State of Illinois indicated in most cases that the wheel loads imposed by traffic were less in magnitude than the loads which when applied statically would produce breaking stresses in the various surface sections. It was noted, also, that failures occurred in many cases only after pavements had been subjected to the action of traffic for several years. As the magnitude of the traffic had not been materially increased, only two feasible explanations could account for these facts: either the strength of the concrete diminished with age, or a sufficient number of applications of load less than that necessary to produce a breaking stress under static load, caused failure.

The first explanation can be discarded since sufficient data is on record to show that the strength of concrete does not diminish with age. Therefore, the only remaining possibility must be that a sufficient number of applications of loads less than those which when applied statically would produce breaking stresses, had caused the failures; in other words, the failures might have been the result of fatigue of the concrete which was caused by a great number of applications of wheel loads. It is conceded by many that steel can fail through fatigue; therefore, it was thought that concrete also might fail because of the same phenomenon.

The theory advanced for this phenomenon is that *concrete will fail under an infinite number of applications of a load of less magnitude than that which normally causes failure.* In other words, loads which cause no apparent damage when applied a few times will cause the concrete to fail when applied a number of times.

Since the Illinois Division of Highways is interested primarily in highways and highway research, the investigation of the phenomenon of fatigue in concrete was considered for the purpose of determining how fatigue affects pavements. The Illinois standard design of concrete surfaces is based on the theory that corners are the least resistant parts of the slabs and act as cantilevers, there being little or no support under their edges; therefore, an apparatus was designed which would produce a like condition on the specimens to be tested for fatigue. Furthermore, as the loads applied to pavements are for the most part distributed through the medium of rubber tires it was thought advisable to subject the specimens to the same type of load. With this in mind Mr. Clifford Older, chief highway engineer of Illinois, designed an apparatus with which to carry on the investigations. The machine was constructed by the Bureau of Tests of the Highway Department in the Spring of 1921.

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[1] Engineer of Tests, Illinois Division of Highways.

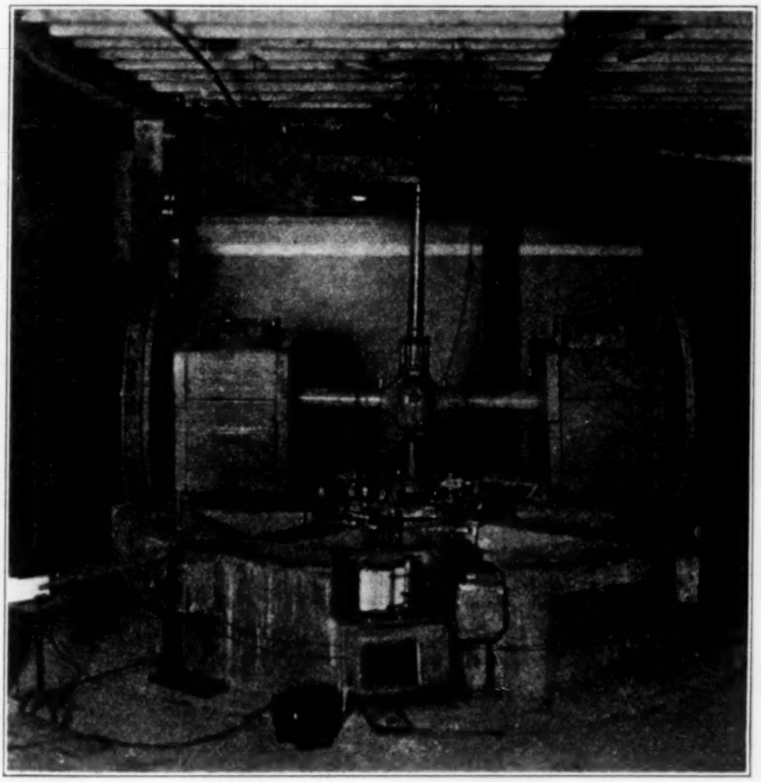

FIG. 1.—Photograph of Machine for Fatigue Testing of Concrete.

DESCRIPTION OF MACHINE.

The fatigue testing machine, see Fig. 1, consists mainly of two parts, that by which the loads are delivered and that which holds the specimens in place. The loading device is made up of the rear axle of a

Ford automobile with the span between wheels lengthened to 7 ft. A vertical housing is attached to the differential casing from which all gears and mechanism have been removed and a 30-in. wooden pulley fastened at the top of this housing. A $1\frac{1}{8}$-in. steel shaft which terminates in a cast-iron socket in a bed plate is held securely on a concrete base by large bolts embedded in the concrete. The upper end of the shaft is held in a fixed support. In the vertical housing are two bearings, a babbit bearing near the top and a roller bearing above the differential casing. This arrangement insures the stability of the machine as the vertical shaft remains fixed and the housing revolves about it. The wheels at the ends of the axles operate on Timken bearings and are encased with 31 by 4 in. tires, which are kept inflated to a constant air pressure of 95 lb. per sq. in. Weight boxes placed equi-distant from the center and fastened to the horizontal housing near the wheels permit the use of a variable load.

The supporting devices which hold the specimens in position consist of a concrete base and two plates between which the specimens are placed. Seven concrete beams are held rigidly at the base plates by means of bolts and strips of steel, one end of each beam projecting out in much the same manner as the spokes radiate from the hub of a wheel. Concrete blocks are placed between each pair of cantilevered beams so as to complete the circular track upon which the wheels carrying the loads may travel, and are so constructed that not over $\frac{1}{2}$ in. of space is left between the block and the beam specimen. The beams are placed so that their surfaces are slightly lower than the surfaces of the adjoining concrete blocks. By capping the beams with a mixture of stucco and cement and striking off the material even with the tops of the concrete blocks, a path of travel is constructed smooth enough to prevent impact.

The loading apparatus is revolved by means of a 2-h.p. motor connected through a countershaft system to the wooden pulley at the top of the vertical housing. This motor produces 20 revolutions of the machine per minute which subjects the beams to 40 applications of load per minute. A counter attached to the apparatus records the actual number of applications of load which the beams receive, and by means of an electrical connection the loading device automatically stops when a beam is broken. This arrangement permits the operation of the machine night and day without the presence of an observer. A graphical attachment records the deflection of any beam under the repeated loads.

TESTS.

The first tests in the fatigue investigation were begun in June of 1921. The specimens upon which the tests were conducted for this series consisted of fifteen 1 : 2 : 3½ concrete beams, 6 in. square by 36 in. in length. In the preparation of the beams, special care was taken; the aggregates were carefully washed, the materials well graded, and the water content determined in an effort to obtain a uniform concrete. Two of the fifteen beams were tested for transverse strength in a universal testing machine to determine the moduli of rupture of the specimens when subjected to static load. Seven of the remaining beams were then placed in the fatigue machine and subjected to a wheel load of 550 lb. This load, which produced a stress of about 50 per cent of the previously determined modulus of rupture, was applied 1,130,976 times to each beam with no failures resulting.

Larger whee and tires were then attached to the machine in order that heavier wheel loads could be applied, after which the beams were subjected to a wheel load of 780 lb. This load produced a stress of 540 lb. per sq. in., or about 61 per cent of the breaking stress as determined by testing the broken parts of the failed beams in the universal testing machine. When a beam failed, a new specimen was put in its place. Seven beams failed under this load with applications ranging in number from 16,782 to 199,836, the majority of failures occurring under less than 50,000 applications. The average age of specimens which failed was 174 days.

Some of the original seven beams which remained intact after 1,130,976 applications of the 550-lb. load and 409,655 applications of the 780-lb. load, were then subjected to a 905-lb. wheel load which produced a stress of approximately 70 per cent of the previously determined maximum. Under this load, the remainder of the fifteen specimens were broken, failure occurring with load applications varying in number from 1,100 to 91,152, the majority breaking at less than 4,000 applications of load.

The results of the first series of tests indicated that concrete will fail under repeated applications of loads which produce stresses 60 per cent or more of the modulus of rupture as determined from tests of transverse strength under static load. They also indicated that repetitions of loads which produce stress less than that noted above, do not cause failure, but apparently increase the strength of the specimen; in other words, there seems to be a critical stress or endurance limit above which repeated applications cause failure of the specimens and below which repeated applications tend to increase the modulus of rupture of concrete.

This latter indication was noted from the fact that the beams which resisted more than 1,000,000 applications of the first and lightest load, resisted more applications of the heavier load than did those beams which were used as replacements and which had not been subjected to previous loading. Furthermore, the moduli of rupture as determined by testing the portions of the failed specimens were somewhat higher than that shown by the specimens which had not been subjected to repetitions of the load.

The procedure used in the second series of fatigue tests was similar to that used in the first except that a 1 : 3 : 5 mix was used for the concrete in place of 1 : 2 : $3\frac{1}{2}$. The change was made so that the effect of fatigue on leaner mixes could be determined. As in the first series, two beams were tested in a universal testing machine so that their moduli of rupture could be determined.

Since all of the beams in the first series failed when subjected to a stress equal to 70 per cent of the maximum, it was decided to use in the second series a load which would produce the same percentage of the previously determined ultimate stress. This load, which was 905 lb., caused all but one of the beams to fail under a comparatively small number of repetitions of load, the greatest number of applications received by any one beam being 1525. The beam which did not fail under the moving wheel load was broken by a 1100-lb. weight applied on its projected end. It was found by testing portions of this beam in the universal testing machine that the section which was stressed under the repeated loading had a modulus of rupture of 772 lb. per sq. in., while the unstressed section showed a modulus of 808 lb. per sq. in. These figures indicate that the beam would have undoubtedly failed had it been subjected to more applications of the same load.

The results obtained on the second series of tests again showed that concrete will fail under repeated applications of a load which produces stress less in magnitude than the modulus of rupture determined by tests for transverse strength under a single application of loading. The results obtained from the first and second series, however, showed that a considerably less number of applications were required to produce failure in the latter test in which the concrete was lean as compared to the former in which the concrete was richer.

To secure additional information on the effect of the proportion of mortar on fatigue, the specimens of a third series of tests were made of 1 : 3 mortar. In this series, again, the moduli of rupture were determined by breaking two beams in the universal testing machine. In this set, also, a wheel load of 780 lb. was used, this load producing a stress equal to 70 per cent of the moduli of rupture. The number of load applications required to cause failure in the specimens of this series varied from 67 to 5,284 repetitions. The results from this series of tests again indicated that concrete will fail through fatigue.

In a fourth series of tests, an attempt was made to determine the relation between the increase in strength of concrete due to age and the deterioration of concrete due to fatigue. This series consisted in testing 45 beams of 1 : 2 : $3\frac{1}{2}$ concrete, divided into three sets of fifteen beams each, upon each set of which different tests were conducted. In all cases in this series, the specimens were placed in the fatigue machine at an age of 30 days.

The first fifteen beams were broken by the repeated application of a 600-lb. wheel load which produced a stress corresponding to 62 per cent of the maximum modulus of rupture under static loading. All the beams of the first set failed under applications which varied in number from 500 to 7,000. The beams of the second set failed under a wheel load of 500 lb. which produced a corresponding stress equal to 51 per cent of that required to break the concrete. The number of load applications varied from 70 to 33,000.

The moduli of rupture of these beams were determined before they were subjected to the moving load by means of a new apparatus instead of the universal testing machine. This new apparatus allowed the test beams to be broken as cantilevers coinciding with the manner in which they are broken in the fatigue machine. In regard to this method of breaking the beams, it should be stated that a difference was noted in the resulting moduli of rupture of the same beams tested by the cantilever apparatus and tested in the universal machine. In practically every case a higher moduli was obtained in the universal machine. The following explanation is given as to the difference of methods of applying the load:

In the universal machine the rate of the application of the load is not uniform. Assuming that the lowest rate of movement of the adjustable head is 0.05 in. per minute, it is plainly evident that the increase in stress in the specimen during the first quarter of the minute is not as great as during the next quarter minute. The rate of the moving of the weight on the counter poise is also increased and it is often the case that when the beam is in the act of failing the weight is run out on the poise arm 1000 lb. or more than is actually necessary to cause failure.

In the cantilevered arrangement, a shot receptacle allows the application of the load to be uniform, the rate of load in this particular apparatus being 100 lb. per minute. This arrangement being more accurate than the universal machine it is planned to discontinue the use of the latter in the tests to determine the breaking strength of the specimens.

After the first two sets of beams were broken, the third set was placed in the fatigue machine and a load of 450 lb. per wheel applied. This load, which produced about 48 per cent of the breaking stress as determined by a test beam in the cantilever apparatus, was imposed upon the beams 2,000,000 times without a single failure taking place. At the age of 90 days, the beams being intact, the load was increased to 500 lb. per wheel. As the strength of the concrete had also increased, due to age, the new load produced a stress of only 50 per cent of the breaking stress. This load was applied 512,000 times and still no failure was brought about. By this time the beams were 120 days old and the load was again increased. The new load applied was 550 lb. per wheel but due to the gain in strength of the concrete, due to age, the additional 50 lb. increased the percentage of breaking stress only one per cent, the new percentage being 51 per cent. After 441,000 applications of this load, no failures taking place in the beam, the load was again increased 50 lb. when the beams were 129 days old. The new load of 600 lb. per wheel caused a stress of 54 per cent of the breaking stress and after 200,000 applications one beam

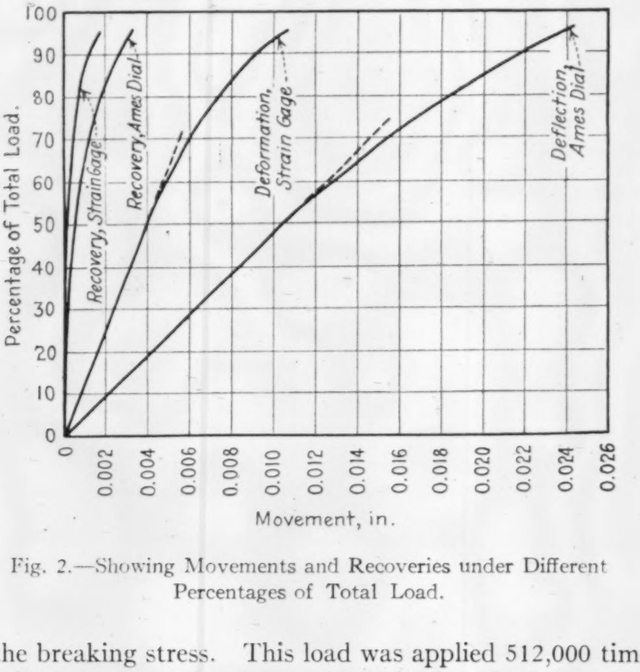

Fig. 2.—Showing Movements and Recoveries under Different Percentages of Total Load.

failed. Other beams continued to fail up to 700,000 applications when the last beam of the set broke.

The results from the three sets of specimens of the fourth series of tests again showed conclusively that there is a limit of endurance in concrete, and that repetitions of stresses above this endurance limit or critical percentage will cause failure while stresses less than the above will not cause failure.

The fourth series showed the same indication as the first in that it required a greater number of load applications to break those specimens which had been subjected to repeated loads than to break replacement specimens, thus showing the increase in strength occasioned by repetitions of loads which produced stresses less than the critical percentage.

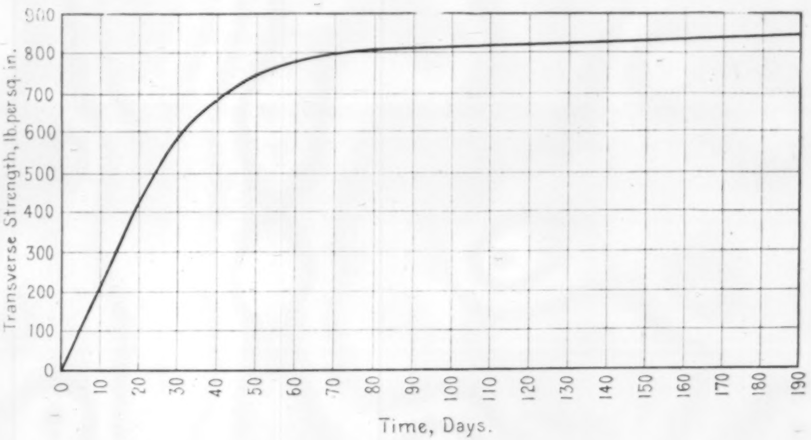

FIG. 3.—Showing Increase in Transverse Strength with Age.

CONCLUSIONS.

It must be considered that the investigation of fatigue has but been started, and the indications up to the present time are at the best but tentative. Considerable additional work will be necessary before definite conclusions can be drawn.

From the first four series of tests, however, it would seem that:

1. Concrete beams will fail under a number of repetitions of loads which produce stress equal to or greater than a certain percentage of that required to cause transverse failure when tested under one application of load;

2. Loads which produce stress less than a certain percentage of the modulus of rupture as determined in the testing machine will not cause

failure on repetitions, but rather, as indicated in the first and fourth series, the strength of the specimen would actually be increased by this condition of load if the load is near this critical percentage;

3. The critical percentage or limit of endurance of the concrete specimens was between 51 and 54 per cent of the modulus of rupture as determined from one application of load;

4. For the same percentage of ultimate strength, a considerably less number of applications of load is required to cause failure in the 1 : 3 : 5 mix specimens than in the 1 : 2 : 3½ mix specimens;

5. Stresses below the limit of endurance do not cause permanent deformation in the specimen;

6. For stresses beyond the limit of endurance, the number of repetitions of load required to produce failure decreases with increase of percentage of stress.

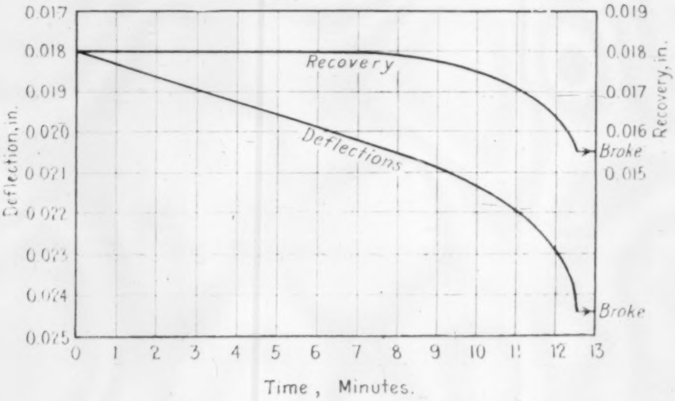

FIG. 4.—Showing Deflections and Recoveries of Beam.

GENERAL INDICATIONS.

Fig. 2 contains curves showing the deflections and recoveries of beams as observed with the use of an Ames dial and a strain gage. It is to be noted that at 50 per cent of the breaking stress the curves deviate from the straight line, indicating that the endurance limit of the concrete has been reached. Curves have been drawn for all the beams used in the tests and the same condition is secured in practically every case.

Fig. 3 contains a curve which shows that after six months, concrete increases in transverse strength but slightly. This curve shows quite markedly how the strength of concrete increases rapidly up to 70 days, after which even up to 190 days very little gain in strength is secured.

Fig. 4 contains curves which are typical examples of the action of all the beams in the fatigue machine. The curve shows the deflections and recoveries of the beam under the wheel load. It is to be noticed that as fatigue takes place the deflections increase while the recoveries decrease.

Table I shows the results obtained on some of the beams in the last test conducted.

Throughout this test it was the intention to use in each set, concrete of the same density and strength. In spite of the precautions taken it is certain that perfectly uniform concrete was not present in the specimens. Without question, this fact has material influence on the results obtained. The modulus of elasticity must be considered if perfectly consistent results are to be obtained in tests of this kind. It appears that there exists a direct relationship between the modulus of elasticity of the concrete and the number of the applications of load necessary to cause the concrete to fail. It is the intention of the Bureau of Tests to conduct an investigation in an effort to arrive at some coefficient that might be used in interpreting the results of the experiments in fatigue to better advantage.

TABLE I.—RESULTS OBTAINED IN FATIGUE TEST OF CONCRETE.

Specimen No.	Load, lb.	Number of Applications.	Load, lb.	Number of Applications.	Load, lb.	Number of Applications.	Load, lb.	Number of Applications.	Stress by Static Load, lb. per sq.in.	Ratio of Fatigue Load Stress to Static Load Stress.
31......	450	2,000,000	500	512,000	550	440,000	600	185,965	707	0.56
33......	450	2,000,000	500	512,000	550	440,000	600	290,325	752	0.53
34......	450	2,000,000	500	512,000	550	440,000	600	665	703	0.56
35......	450	2,000,000	Removed	......	...	......	...	......	767	....
36......	450	2,000,000	Removed	......	...	......	...	......	670	....
39......	...	....	...	......	...	......	...	......	628	....
40......	...	....	...	......	...	......	...	......	747	....
41......	...	......	...	......	...	......	...	......	537	....
43......	...	....	500	512,000	550	440,000	600	303,654	685	0.58
44......	...	....	500	512,000	550	187,477	Broke	......	678	0.54
45......	...	....	500	512,000	550	440,000	600	234,303	783	0.51

FUTURE INVESTIGATIONS.

The tests already conducted in fatigue of concrete point out that a load which stresses the concrete below its endurance limit causes a deflection of the specimen with a recovery of exactly the same amount when the load is released. A load which causes a stress above the endurance limit was found to cause a deflection greater than a recovery subsequent to the removal of the load. It is thought that a continued action such as this would necessarily generate heat at the stressed section, which might have a bearing on the action of fatigue and the strengthening effect of the concrete. A thorough study of this heat action is now planned. By means of a thermo-couple it is expected that it will be possible to determine the increase in temperature at the stressed section due to the deflections and recoveries produced by loads, the magnitude of which causes a stress that approaches or is above the endurance limit.

Investigations are being planned with a machine to determine the action of static and impact fatigue. In this way it is hoped that all conditions affecting fatigue can be brought together and studied as one. A static machine has already been constructed and is now being used in conjunction with the repeated load machine. The machine consists of a heavy square column of concrete with slots on each of the four sides to allow the insertion of an end of a beam. The end is then secured rigidly and through a slot arrangement the beams are loaded at their projected ends. Dials and strain gages permit the reading of deflections and deformations. The study of static fatigue has not progressed far enough to permit the stating of definite results.

The impact fatigue machine is constructed in such a manner as to bring about the same relation between the unsprung and sprung weights as exists in an ordinary truck. Every precaution has been taken in the building of this machine to duplicate the conditions of impact as produced in actual traffic. In connection with the impact and static tests it is planned to conduct experiments with combined static and impact conditions. The beams are to be subjected to different percentages of static stresses well within the working load and a small impact load then applied. This test should develop how the combined loads affect the life of concrete.

Further investigations of the theory that fatigue takes place in the mortar are to be made with a miniature repeated load machine of the same design as the large machine. This new apparatus will be used to test specimens 1 by 1 by 10 in. It is expected that considerable information will be secured through the use of this small model.

Though the repeated load fatigue machine has been in operation almost continuously for the past nine months it is realized that there is much more to be learned about fatigue of concrete. The results obtained have given an insight as to what might be expected and further investigations can now be conducted with more confidence in the effort to secure data of a more definite and valuable nature.

DISCUSSION

Mr. Hatt.

MR. W. K. HATT.—This is an instance of one of three investigations of this nature which were started by different persons about the same time, in Illinois, at Purdue University and by Dean A. N. Johnson of the University of Maryland. At Purdue University we are investigating the strength of concrete under reversed stresses. The specimen is a beam of 1 : 2 mortar, placed upright, and bent back and forth by means of a straining beam fixed to the top. Load is placed alternately on this straining beam, the load being operated by a walking beam. An Ames dial is put on each side of the specimen, and as the specimen bends back and forth the deflections are measured. It is very plain that as the number of reversals increases, the deformation increases until finally the beam breaks. A peculiar effect is noticed in that when the power is shut off over night there is a recovery of the concrete.

The observations made enable us to determine what is going on in the concrete. For instance, in a cycle of bending back and forth in compression and then in tension there will be a set in compression followed by a set in tension. It is probable that the fatigue element is due to the working of the concrete back and forth within its plastic range of plus and minus sets. Of course what goes on there is a threefold operation, the fatiguing of the concrete, the increase in strength of the beam with age (as some of these are in the machine three and four weeks) and the possible increase of strength due to the rise of temperature caused by the working of the concrete back and forth.

Dean A. N. Johnson, of the University of Maryland, who has a singular genius in devising and very great care in using delicate apparatus, has avoided some of the difficulties by using beams which are one year in age. Two beams are placed vertical and shackled together at both ends. At the center of the length is an eccentric shaft by which the beams are spread apart to 0.002 in. as measured by a dial. The beams are removed from the fatigue machine at intervals and changes in elastic properties are measured in a static machine. So far, he has been able to put about two million applications of a load on such beams. He is working, not with stress, but with deformation.

I think all three investigations at present seem to show a fatigue limit of about 52 per cent of the ultimate strength. Above that, the beams break rather rapidly. With less stress than 52 per cent there is apparently a horizontal line connecting stress and number of applications.

RELATION OF YIELD VALUE AND MOBILITY OF PAINTS TO THEIR SO-CALLED PAINTING CONSISTENCY.

By James E. Booge,[1] Eugene C. Bingham,[2] and Herbert D. Bruce.[3]

Introduction.

By James E. Booge.[4]

A property of paints of major importance is their "*consistency.*" Agreement with or departure from "painting consistency" governs their ease of application in the hands of the painter. The most usual methods of determining the consistency are the spatula and brushing tests: In the former the resistance to stirring in the can and ease of flow from the spatula are observed; in the latter paint-outs are made on panels with relatively small brushes. The following disadvantages of these tests are generally acknowledged: (1) They possess a low degree of precision; (2) interpretation of the results depends entirely on the experience and judgment of the operator; and (3) the results cannot usually be recorded in a form available for future comparison.

The work of Bingham and Green[5] proved that paints possess a yield value and must, therefore, be classed as plastic solids. It follows that their consistency depends on two presumably independent constants: the yield value and mobility. These may be determined with a high degree of precision; the results may be duplicated by different observers at different laboratories and can be expressed as numbers, available for later comparison. Hence none of the disadvantages inherent in the usual methods of determining consistency apply to plastometer results. The present study was, therefore, undertaken by Dr. Bingham with the object of finding out whether a sufficiently simple relation exists between the results of the usual consistency determinations on the one hand, and the plastometer determinations on the other, to indicate the possibility of adoption of the latter method as a *test for consistency*.

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[1] Research Chemist, E. I. du Pont de Nemours and Co.

[2] Professor of Chemistry, Lafayette College.

[3] du Pont Fellow, Lafayette College.

[4] Secretary of the Umpire Committee, see p. 421.

[5] E. C. Bingham and Henry Green, "Paint, a Plastic Material and Not a Viscous Liquid: the Measurement of its Mobility and Yield Value," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II, p. 640 (1919).

The program for the work has comprised carrying out both types of determinations on samples of the same paints. Little difficulty has been encountered in Dr. Bingham's laboratory in the obtainment of accurate plastometer measurements; on the other hand it is obviously difficult to secure a similarly reliable verdict on the consistency judged by the ordinary tests. To overcome this obstacle an appeal was made to the following men to serve as members of an "Umpire Committee," with a very generous response.

Mr. Henry A. Gardner, Institute of Paint and Varnish Research, *Chairman*.
Dr. A. H. Sabin, National Lead Co.
Mr. Percy H. Walker, U. S. Bureau of Standards.
Mr. F. P. Ingalls, John W. Masury and Son.
[1]Mr. L. P. Nemzek, E. I. du Pont de Nemours and Co.
[1]Mr. L. E. Kelly, E. I. du Pont de Nemours and Co.
[1]Dr. J. E. Booge, E. I. du Pont de Nemours and Co., *Secretary*.

The average verdict of the above committee on painting consistency may fairly be regarded as accurately representing present standards.

Seven widely varying types of paint were chosen: flat white, outside white, anti-rust black, mill white gloss, white enamel, black enamel, and anti-rust red. The general formulas of these paints appear in Table I. Three samples of each of the first three paints were prepared of somewhat varying consistency and one sample of the other four paints—making thirteen samples in all. The object was to cover the field in a preliminary way; concentration on one or two types of paint may well follow later. After thorough mixing of each batch, pint cans were filled and distributed to the members of the committee, four cans being reserved for Dr. Bingham's use. The results obtained by members of the Umpire Committee will be discussed in this preliminary section of the paper.

The two tests used in the different laboratories have already been referred to. In one laboratory,[2] it was found that the use of small panels in a horizontal position gave poor results. Panels 6 by 18 in. were then used in a vertical position. "The brush work was done by three men on eleven of the samples and two men on the other two samples. . . . Method *B* (*i. e.*, the brush method) was used once on October 25, 1921, and again on November 2, 1921, the same men making the test on the two days. It should be stated that in all cases the operators made their comments without consultation with one another. . . . Before making the tests on November 2, 1921, a white lead-zinc oxide-linseed oil paint was mixed to what was considered the most satisfactory brushing consistency by all three observers and each observer painted out this paint as a control." In a second laboratory[1] independent verdicts were reached by Messrs. Ekey, Mitchell, and Brett, and the results averaged. The verdicts of the other committee members likewise represent tests by the member himself with cooperation of one or more other men in the same laboratory.

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[1] One vote only for du Pont representatives.

[2] Laboratory of P. H. Walker.

TABLE I.—PAINT FORMULAS.

Paint.	Pigment, per cent.	Oil, per cent.	Thinner, per cent.	Drier, per cent.	"Emulsifying Agent," per cent.
Flat White *C*	57.00	16.04	26.22	0.12	0.66
Flat White *A*	63.36	13.54	22.94	0.01	0.59
Flat White *B*	66.31	12.83	20.24	0.01	0.60
Anti-rust Black *C*	31.10	55.74	12.57	0.59	....
Anti-rust Black *A*	34.55	53.67	11.25	0.53	....
Anti-rust Black *B*	37.50	51.90	10.12	0.48	....
Outside White *C*	57.00	31.63	10.69	0.68	....
Mill White Gloss	61.70	24.50	13.10	0.70	....
Outside White *A*	63.33	31.90	4.60	0.17	....
White Enamel	44.10	33.60	22.16	0.14	....
Outside White *B*	65.15	30.56	4.14	0.15	....
Black Enamel	3.12	43.68	51.85	1.47	....
Anti-rust Red	41.10	48.70	9.70	0.50	....

The basis of judgment in another laboratory[2] was as follows: "This judgment is based on the fundamental fact that when applied with a soft brush on a non-absorptive surface (*e.g.*, smooth iron or tin plate) the paints do not run or show separation of pigment and vehicle even when applied in a full coat. The term 'full coat' is admittedly indefinite but represents an average between the extreme of no brushing out and extreme brushing out."

The committee members were requested to interpret their results in terms of agreement with or departure from ideal painting consistency. It is well known that the term "ideal painting consistency" is hard to define and necessarily varies from one type of paint to another. In fact it is this very situation which makes the verdict of a number of experts necessary. This variation in the standard of reference is clearly discussed in the report of Mr. Ingalls:

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[1] Laboratory of A. H. Sabin.

[2] Laboratory of F. P. Ingalls.

"*Anti-rust Black.*—Paints of this kind are usually applied with as little labor as possible. They are frequently 'slapped on' and as a result the coat is relatively thick and would be excessively so if the paint were not comparatively thin.

"*Anti-rust Red.*—This sample is a little too thin in its initial state but by reason of the fairly rapid evaporation of the volatile thinner . . . the consistency thickens under the brushing out to a uniform coat. The net result is that the paint must be classified as thin but passable.

"*Outside Whites.*—We rather expect different judges to differ on this paint because linseed oil paint can be used with a brush up to a consistency of semi-paste and many painters are quite accustomed to using heavy white paints purposely so thinned, in order to get extra hiding power."

The possibility that the paint samples tested, although taken from the same batch, changed in consistency in the can must be referred to. The samples were sent out in September, 1921, and examined by the members of the committee by January 1, 1922. The plastometer determinations extended over a longer period to February, 1922. The best evidence that no serious changes occurred is the general agreement between plastometer determinations on duplicate cans of paint at different times, often several months apart. This will be referred to later.

The problem of averaging the verdicts of the Umpire Committee was solved by first converting them to a numerical basis. This conversion was made as follows: The "best" consistency was graded 0. Paints thicker than 0 were graded +1, +2, or +3. Very slightly thick paints which are definitely thicker than OK but still just "passing" and directly usable "as is" are graded +1. Slightly thick paints not passing or not recommended for direct use even though possibly usable with certain precautions, such as a very stiff brush, are graded as +2. Similarly, deviations from OK consistency on the thin side are indicated by −1, −2, and −3. The following table summarizes the above discussion.

TABLE II.—KEY TO NUMERICAL GRADING FOR CONSISTENCY.

CONSISTENCY.	GRADING.[1]
Best Painting consistency	0
Very slightly thick, just passing	+1
Slightly thick, not passing	+2
Definitely thick	+3
Very slightly thin, just passing	−1
Very slightly thin, not passing	−2
Definitely thin	−3

The use of these numbers has the additional advantage of permitting ready condensation and tabulation of grading.

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[1] In addition, half steps between these gradings are sometimes necessary.

The findings of the Umpire Committee are summarized in Table III. The averages also appear in the last column.

Two points are worthy of attention: First, the range of consistency in the paint samples is rather small. None departs from the limits met in cans on dealers' shelves and all but two are given a passing grading; second, the verdicts of the individual committee members agree more closely than might have been anticipated. In seven cases the verdicts of all five members are in as close agreement as could reasonably be expected. Paints Nos. 1, 2, 5, 8, 9, and 12 were unanimously graded passing and Paint No. 3 not passing. In four cases, Paints Nos. 4, 6, 7, and 13, one member disagreed with the other four. On Paint No. 11 there was fair agreement, two members judging it just passing, the others not quite passing. The remaining sample, Paint No. 10, caused considerable disagreement. This may possibly be due to a change in consistency in the can.

TABLE III.—RESULTS OF CONSISTENCY TESTS ON PAINT SAMPLES.

Paint Sample.	Consistency Judged by Member.					Average Verdict.	Extreme Variation.
	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.		
1—Flat White *C*	0	−0.5	−0.5	−0.3	0	−0.3	0.5
2—Flat White *A*	0	+0.5	0	+0.3	+1	+0.4	1.0
3—Flat White *B*	+1.5	+3.0	+2.0	+1.7	+3.0	+2.2	1.5
4—Outside White *C*	−1.0	−0.5	−0.5	−2.0	0	−0.8	2.0
5—Outside White *A*	0	0	0	−1.0	+1.0	0	2.0
6—Outside White *B*	0	+0.5	0	0	+2.0	+0.5	2.0
7—Anti-rust Black *C*	−1.0	−0.5	−0.5	−2.0	0	−0.8	2.0
8—Anti-rust Black *A*	0	0	0	0	+1.0	+0.2	1.0
9—Anti-rust Black *B*	0	+0.5	0	−0.3	+0.5	+0.1	0.8
10—Mill White Gloss *A*	0	+1.0	0	+3.0	+2.0	+1.2	3.0
11—White Enamel *A*	+1.0	+1.0	+1.5	+2.3	+1.5	+1.5	1.3
12—Black Enamel *A*	0	0	0	−0.3	−1.0	−0.3	1.0
13—Anti-rust Red *A*	0	−1.0	0	−1.3	−1.0	−0.7	1.3

It may be concluded from the above that with due allowance for the inaccuracy of the usual methods of judging the consistency of paints the average verdicts can be taken as a satisfactory basis for comparison with Dr. Bingham's plastometer measurements. It may be added that at Dr. Bingham's request the paints were sent him in cans marked by numbers only and further information was withheld until the plastometer measurements were made and the results transmitted to the secretary of the committee.

EXPERIMENTAL.

BY HERBERT D. BRUCE.

For a constant-pressure regulator there has always before been used, in conjunction with the Bingham and Green plastometer, a

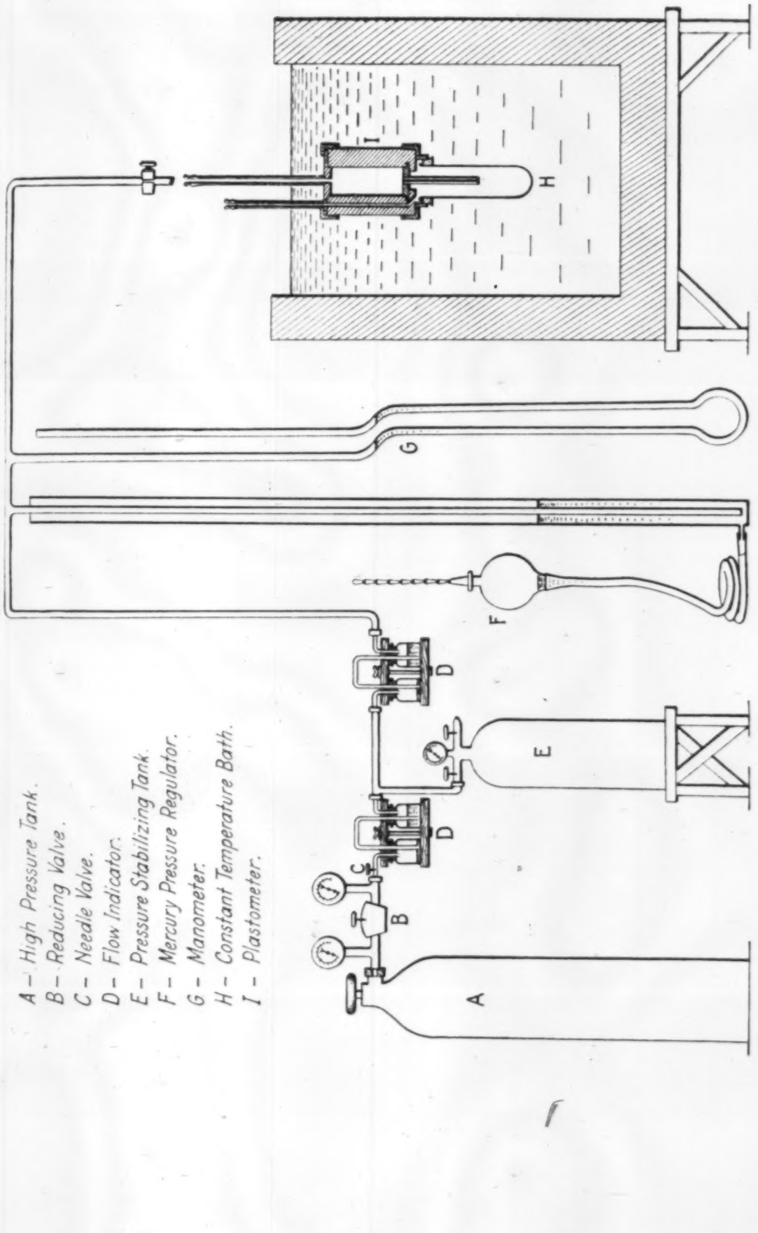
A – High Pressure Tank.
B – Reducing Valve.
C – Needle Valve.
D – Flow Indicator.
E – Pressure Stabilizing Tank.
F – Mercury Pressure Regulator.
G – Manometer.
H – Constant Temperature Bath.
I – Plastometer.
A
B
C
D
E
D
F
G
H
I

FIG. 1.—Plastometer.

series of stand-pipes containing water.[1] A single pipe containing mercury was never found feasible because it was very difficult to regulate the needle valve to allow a small stream of air to bubble through regularly. At the end of the small inner pipe, a large bubble of air would collect and hang. When this bubble did break and pass up through the mercury, a too considerable variation in the pressure was indicated by the manometer. However, the single pipe has the advantages of being less bulky, less expensive, and more convenient, and efforts were made to adapt it to practical use. Small flow indicators were installed into the air line as shown in Fig. 1. By means of these the operator can see when a very slow stream of air is passing through the system. Also, the end of the inner iron pipe that dips into the mercury was amalgamated with sodium amalgam so that the mercury wets the sides. Small bubbles of gas then passed over at regular intervals, just as with a water regulator, and the manometer showed negligible fluctuation. The amalgam may disappear from the iron pipe after some months, but the addition of a small amount of metallic sodium to the mercury has been found beneficial.

The regulator, *F*, Fig. 1, which we have been using in this work consists of a large pipe 3.3 cm. in outside diameter, and inner pipe of 1.1 cm. outside diameter, and about 9 kg. of mercury. This amount will give a maximum pressure of about 2 atmospheres.

It has been found necessary to have in the air line a tank, *E*, to act as a pressure-stabilizing reservoir, thus preventing a sudden fall in pressure when the stop-cock leading to the container, *I*, is opened. It was found that a tank of large capacity was not only unnecessary, but used up compressed air at an undesirable rate. A small tank, holding 17 liters, was substituted for the larger one, and this equalized the pressure just as satisfactorily. This tank had a second valve opening directly to the air, which was found to be very convenient.

All samples of paint were thoroughly stirred with a spatula in the can for from 20 to 30 minutes to insure homogeneity of the pigment and vehicle. A portion, about 100 cc., was then rubbed with the finger tips through a 300-mesh copper gauze to remove any coarse particles which might obstruct the capillary. This sample, in a glass weighing bottle, was set into the water bath at 25° C. for a period of over 1 hour, to allow the paint to come to the exact temperature. This paint was again stirred a little with a small spatula, poured into the plastometer, and the rates of flow through the capillary tube at various pressures were measured. The efflux was always ascertained

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[1] *Loc. cit.*

TABLE IV.—FLAT WHITE C, SAMPLE 24.

$f = 551.2$ November 18, 1921.
$\mu = 1.223$ 25° C.
$\rho = 1.663$ Capillary 10.
$M/t = -0.0025196 + 0.0000045714\ F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC. OBSERVED.	EFFLUX, G. PER SEC. CALCULATED.	DIFFERENCE, PER CENT.
A	1918	0.00605	0.006248	−3.29
	1917	0.00649	0.006244	3.96
	1916	0.00621	0.006239	−0.47
	1915	0.00618	0.006235	−0.87
B	2296	0.00796	0.007976	−0.26
	2295	0.00796	0.007972	−0.28
C	2569	0.00929	0.009224	0.72
	2576	0.00917	0.009256	−0.89
D	2856	0.01068	0.01054	1.39
	2854	0.01056	0.01053	0.29
E	2984	0.01112	0.01112	0.00
	2983	0.01113	0.01112	0.15
F	3131	0.01173	0.01179	−0.54
	3130	0.01174	0.01179	−0.43
Average				0.97

TABLE V.—FLAT WHITE C, SAMPLE 2.

$f = 591.4$ October 1, 1921.
$\mu = 1.076$ 25° C.
$\rho = 1.660$ Capillary 12.
$M/t = -0.023563 + 0.000039840\ F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC. OBSERVED.	EFFLUX, G. PER SEC. CALCULATED.	DIFFERENCE, PER CENT.
C	2493	0.07590	0.07573	0.22
	2489	0.07588	0.07560	0.37
D	1940	0.05330	0.05373	−0.80
	1938	0.05320	0.05365	−0.84
E	1581	0.04000	0.03942	1.47
	1599	0.04002	0.04014	−0.30
*F**	953	0.01740	0.01440	20.83*
	951	0.01631	0.01432	14.70
	949	0.01720	0.01425	20.70
*G**	653	0.00667	0.00245	172.24*
	598	0.00597	0.00221	170.13
	605	0.00651	0.00237	174.68
Average				0.67

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* Observations marked by an asterisk (*) were not used in obtaining the calculated equation. Explanation follows Table XXXIV.

TABLE VI.—FLAT WHITE A, SAMPLE 26.

$f = 711.1$ November 24, 1921.
$\mu = 0.661$ 25° C.
$\rho = 1.706$ Capillary 12.
$M/t = -0.017886 + 0.000025152\,F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC.		DIFFERENCE, PER CENT.
		OBSERVED.	CALCULATED.	
A*	1209	0.01394	0.01252	11.34*
	1207	0.01403	0.01247	12.51
B	1914	0.02899	0.03025	−4.35
	1918	0.03060	0.03036	0.79
	1914	0.03028	0.03025	0.10
C	2440	0.04450	0.04348	2.35
	2438	0.04360	0.04343	0.39
	2452	0.04358	0.04379	−0.48
D	3268	0.06474	0.06431	0.67
	3261	0.06435	0.06413	0.34
	3273	0.06402	0.06444	−0.66
	3274	0.06421	0.06446	−0.39
E	3822	0.07865	0.07824	0.52
	3829	0.07800	0.07942	−1.82
Average				1.07

TABLE VII.—FLAT WHITE A, SAMPLE 1.

$f = 860$ September 24, 1921.
$\mu = 0.650$ 25° C.
$\rho = 1.704$ Capillary 12.
$M/t = -0.021240 + 0.000024700\,F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC.		DIFFERENCE, PER CENT.
		OBSERVED.	CALCULATED.	
(A)	3987	0.07801	0.07724	1.00)
	3982	0.07962	0.07721	3.12)
	3976	0.07902	0.07697	2.70)
	3973	0.07871	0.07689	2.37)
(B)	3748	0.07471	0.07134	4.72)
	3743	0.07401	0.07121	3.93)
	3738	0.07391	0.07109	3.97)
C	3624	0.06860	0.06827	0.48
	3639	0.06700	0.06864	−2.39
	3634	0.06860	0.06852	0.12
D	3257	0.05879	0.05921	−0.70
	3252	0.05867	0.05909	−0.71
E	2496	0.04076	0.04041	0.87
	2491	0.04036	0.04029	0.17
F*	1707	0.02274	0.02092	8.70*
	1704	0.02268	0.02085	8.78
G*	922	0.00641	0.00153	318.95*
	921	0.00591	0.00151	291.39
	920	0.00591	0.00148	299.32
Average				0.88

TABLE VIII.—FLAT WHITE A, SAMPLE 39.

$f = 704.5$ January 6, 1922.
$\mu = 0.640$ 25° C.
$\rho = 1.708$ Capillary 11.
$M/t = -0.017302 + 0.000024562\ F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC. OBSERVED.	EFFLUX, G. PER SEC. CALCULATED.	DIFFERENCE, PER CENT.
A	1696	0.02450	0.02435	0.58
	1691	0.02435	0.02423	0.50
B	2466	0.04309	0.04327	−0.40
	2439	0.04249	0.04260	−0.27
C	3332	0.06471	0.06454	0.27
	3355	0.06524	0.06510	0.21
D	4176	0.08537	0.08527	0.12
	4188	0.08514	0.08556	−0.49
Average				0.36

TABLE IX.—FLAT WHITE B, SAMPLE 27.

$f = 1247.4$ November 25, 1921.
$\mu = 0.4091$ 25° C.
$\rho = 1.736$ Capillary 12.
$M/t = -0.019760 + 0.000015841\ F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC. OBSERVED.	EFFLUX, G. PER SEC. CALCULATED.	DIFFERENCE, PER CENT.
(*A*)	4127	0.04866	0.04562	6.66)
	4123	0.04830	0.04555	6.04)
(*B*)	3896	0.04512	0.04196	7.53)
B	3907	0.04181	0.04213	−0.77
	3902	0.04230	0.04205	0.59
	3892	0.04165	0.04189	−0.58
C	4125	0.04546	0.04558	−0.26
	4120	0.04583	0.04550	0.73
D	3001	0.02791	0.02778	0.47
	2989	0.02709	0.02759	−1.85
	3004	0.02723	0.02783	−2.20
E	2807	0.02501	0.02471	1.21
	2803	0.02489	0.02464	1.01
F	2431	0.01915	0.01875	2.13
	2428	0.01885	0.01870	0.80
*G**	2142	0.01469	0.01417	3.67*
	2135	0.01440	0.01406	2.42
Average				1.05

First three measurements were high. Then setting may have occurred and efflux values dropped.

by weighing on the analytical balance and not by measuring the volume extruded or by calculating from the drop weights.

The method of drop weights used by Bingham and Green[1] was not employed because it failed to give consistent results. With every paint with which we worked, we found that the weight of the drop bore no simple relationship to the rate of flow and therefore could not be used to calculate the efflux values. This does not necessarily invalidate the claims of Bingham and Green, for had other factors been constant for every determination, a linear relationship might have resulted. Thus, the area of the capillary tip, from which the drop falls, may not always have been the same. It was noticed repeatedly that those drops which formed rapidly and fell without first spreading over the capillary tip were smaller than those which dropped from a larger surface.

TABLE X.—FLAT WHITE B, SAMPLE 25.

$f = 1443.6$ November 22, 1921.
$\mu = 0.4778$ 25° C.
$\rho = 1.738$ Capillary 12.
$M/t = -0.026737 + 0.0000185205\ F$

Observation.	Shearing Stress, dynes per cm.^{2}	Efflux, g. per sec. Observed.	Efflux, g. per sec. Calculated.	Difference, per cent.
A	4121	0.05029	0.04959	1.41
	4117	0.04940	0.04951	−0.22
	4112	0.04904	0.04942	−0.77
B	3903	0.04542	0.04555	−0.29
	3902	0.04544	0.04553	−0.20
C	3619	0.04029	0.04029	0.00
	3615	0.03999	0.04021	−0.55
D	3280	0.03396	0.03401	−0.15
	3267	0.03343	0.03377	−1.02
E	2911	0.02753	0.02718	1.29
	2927	0.02775	0.02747	1.02
*F**	2489	0.02080	0.01936	7.44*
	2487	0.02050	0.01932	6.11
*G**	2128	0.01549	0.01267	22.26*
	2126	0.01492	0.01264	18.04
	2124	0.01481	0.01260	17.54
*H**	1742	0.00954	0.00553	72.52*
	1740	0.00936	0.00549	70.49
Average				0.63

We give herewith the average drop weights for Outside White

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[1] *Loc. cit.*

TABLE XI.—FLAT WHITE B, SAMPLE 8.

f = 1302.0 October 15, 1921.
μ = 0.4258 25° C.
ρ = 1.735 Capillary 12.
$M/t = -0.021459 + 0.000016477\ F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC.		DIFFERENCE, PER CENT.
		OBSERVED.	CALCULATED.	
A	4001	0.04411	0.04447	−0.81
	3998	0.04461	0.04442	0.42
B	3815	0.04214	0.04140	1.79
	3812	0.04140	0.04135	0.12
	3808	0.04140	0.04129	0.26
C	3311	0.03236	0.03310	−2.24
	3308	0.03296	0.03305	−0.27
	3304	0.03319	0.03298	0.64
D	2945	0.02719	0.02707	0.44
	2942	0.02680	0.02702	−0.81
	2939	0.02672	0.02697	−0.93
E	2513	0.02007	0.01995	0.60
	2510	0.02000	0.01990	0.50
*F**	1904	0.01140	0.00991	15.04*
	1902	0.01114	0.00988	11.28
	1901	0.01117	0.00986	13.29
*G**	1421	0.00543	0.00195	178.46*
	1420	0.00531	0.00194	173.71
	1419	0.00531	0.00193	175.13
Average				0.76

TABLE XII.—ANTI-RUST BLACK C, SAMPLE 4.

f = 345.8 December 21, 1921.
μ = 1.621 25° C.
ρ = 1.101 Capillary 10.
$M/t = -0.0015315 + 0.0000044292\ F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC.		DIFFERENCE, PER CENT.
		OBSERVED.	CALCULATED.	
A	3134	0.01231	0.01235	−0.32
	3132	0.01239	0.01234	0.41
B	2865	0.01121	0.01116	0.46
	2854	0.01108	0.01111	−0.31
C	2536	0.009686	0.009701	−0.15
	2522	0.009627	0.009639	−0.12
D	2171	0.008114	0.008084	0.37
	2170	0.008096	0.008080	0.20
E	1821	0.006529	0.006534	−0.08
	1820	0.006501	0.006530	−0.45
F	1535	0.005270	0.005267	0.06
	1528	0.005225	0.005236	−0.21
Average				0.26

Table XIII.—Anti-Rust Black C, Sample 36.

$f = 332.4$ January 2, 1922.
$\mu = 1.647$ 25° C.
$\rho = 1.010$ Capillary 10.
$M/t = -0.0014875 + 0.0000044752\ F$

Observation.	Shearing Stress, dynes per cm².	Efflux, g. per sec. Observed.	Efflux, g. per sec. Calculated.	Difference, per cent.
A	3222	0.01293	0.01293	−0.04
	3220	0.01293	0.01292	0.06
B	2963	0.01188	0.01177	0.90
	2954	0.01169	0.01173	−0.33
C	2647	0.01035	0.01036	−0.09
	2645	0.01036	0.01035	0.06
D	2258	0.008557	0.008617	−0.70
	2267	0.008678	0.008658	0.23
E	1941	0.007162	0.007199	−0.52
	1938	0.007125	0.007195	−0.84
F	1582	0.005671	0.005592	1.41
	1572	0.005566	0.005547	0.34
G	1242	0.004055	0.004071	−0.39
	1239	0.004054	0.004057	−0.07
Average				0.43

Table XIV.—Anti-Rust Black A, Sample 30.

$f = 307.0$ December 14, 1921.
$\mu = 1.0517$ 25° C.
$\rho = 1.097$ Capillary 10.
$M/t = -0.00087809 + 0.0000028603\ F$

Observation.	Shearing Stress, dynes per cm.²	Efflux, g. per sec. Observed.	Efflux, g. per sec. Calculated.	Difference, per cent.
A	3108	0.008003	0.008012	−0.11
	3107	0.008005	0.008009	−0.05
B	2780	0.007099	0.007074	0.35
	2779	0.007070	0.007071	−0.01
C	2433	0.006059	0.006110	−0.84
	2433	0.006088	0.006110	−0.36
D	2148	0.005276	0.005266	0.19
	2147	0.005256	0.005263	−0.13
E	1839	0.004403	0.004382	0.48
	1826	0.004353	0.004345	0.18
F	1560	0.003594	0.003584	0.28
	1554	0.003523	0.003567	−1.25
Average				0.35

Paint Sample 37, corresponding to the observations *A* to *G*, respectively, in Table XVII: 36.74, 38.04, 36.61, 36.41, 38.35, 37.91, 38.67 mg. These numbers show wide variation but there is no consistent trend as the shearing force decreases. The method adopted of weighing the total efflux gives quite consistent results as may be seen from the percentage differences between the observed and calculated values given in the last column of Table XVII. To save space, other examples like the above are not given but this one is taken at random and regarded as typical.

TABLE XV.—ANTI-RUST BLACK B, SAMPLE 5.

$f = 372.7$ November 8, 1921.
$\mu = 0.7987$ 25° C.
$\rho = 1.185$ Capillary 11.
$M/t = -0.0079285 + 0.000021271\ F$

Observation.	Shearing Stress, dynes per cm.²	Efflux, g. per sec. Observed.	Efflux, g. per sec. Calculated.	Difference, per cent.
A	6613	0.1341	0.1327	1.02
	6613	0.1328	0.1327	0.06
	6613	0.1328	0.1327	0.01
B	5934	0.1183	0.1183	−0.01
	5928	0.1181	0.1182	−0.06
C	5049	0.09879	0.09947	−0.69
	5041	0.09942	0.09930	0.12
	5051	0.09886	0.09951	−0.66
D	4089	0.07885	0.07905	−0.25
	4096	0.07884	0.07920	−0.46
E	3519	0.06641	0.06692	−0.77
	3528	0.06613	0.06712	−0.15
F	2866	0.05270	0.05306	−0.68
	2860	0.05248	0.05291	−0.89
G	2262	0.04011	0.04019	−0.20
	2248	0.04093	0.03989	2.60
	2242	0.04049	0.03976	1.84
	2237	0.04053	0.03965	2.22
*H**	1511	0.02499	0.02421	3.22*
	1509	0.02542	0.02417	5.17
*I**	1097	0.01726	0.01541	12.01*
	1093	0.01709	0.01532	11.55
Average				0.70

Moreover, if the capillary of the plastometer is not set each time in a perfectly vertical position, the drops appear to slip off the capillary at more or less of an angle. These drops are smaller than

TABLE XVI.—ANTI-RUST BLACK B, SAMPLE 18.

$f = 385.3$ December 6, 1921.
$\mu = 0.7832$ 25° C.
$\rho = 1.183$ Capillary 10.
$M/t = -0.00092162 + 0.0000023920\,F$

Observation.	Shearing Stress, dynes per cm.^{2}	Efflux, g. per sec. Observed.	Efflux, g. per sec. Calculated.	Difference, per cent.
A*	811	0.001343	0.001018	31.92*
	811	0.001311	0.001018	28.78
B*	1117	0.001978	0.001750	13.03*
	1117	0.001921	0.001750	9.77
C*	1468	0.002707	0.002590	4.52*
	1462	0.002671	0.002575	3.73
D	1751	0.003334	0.003267	2.05
	1750	0.003275	0.003264	0.34
E	2037	0.003984	0.003951	0.08
	2036	0.003912	0.003948	−0.92
F	2515	0.005109	0.005094	0.29
	2514	0.005003	0.005092	−1.78
G	2884	0.006049	0.005977	1.20
	2883	0.006165	0.005974	3.20
	2881	0.005863	0.005970	−1.83
H	3119	0.006439	0.006539	−1.55
	3118	0.006480	0.006537	−0.88
Average				1.28

TABLE XVII.—OUTSIDE WHITE C, SAMPLE 37.

$f = 174.4$ December 19, 1921.
$\mu = 0.5818$ 25° C.
$\rho = 1.869$ Capillary 10.
$M/t = -0.0004708 + 0.00000269902\,F$

Observation.	Shearing Stress, dynes per cm.^{2}	Efflux, g. per sec. Observed.	Efflux, g. per sec. Calculated.	Difference, per cent.
A	3160	0.008050	0.008058	−0.10
	3165	0.008104	0.008072	0.40
B	2828	0.007144	0.007162	−0.25
	2827	0.007171	0.007159	0.17
C	2541	0.006377	0.006387	−0.16
	2540	0.006379	0.006385	−0.09
D	2175	0.005367	0.005400	−0.62
	2174	0.005420	0.005397	0.43
E	1889	0.004685	0.004628	1.23
	1888	0.004603	0.004625	−0.48
F	1565	0.003711	0.003753	−1.13
	1564	0.003766	0.003750	0.43
G*	1203	0.002906	0.002776	4.68*
	1202	0.002883	0.002774	3.93
Average				0.46

those that fall from the perfectly horizontal surface. The decrease has been observed to fall to as low as 0.7 of the full drop.

When the paint is very thin or the rate of flow is very low, the drops appear to approach their full size, but this condition was seldom realized and the drop-weight method seemed impracticable for our use. Accordingly, all effluxes were made by direct weighing after each flow.

Table XVIII.—Outside White C, Sample 3.

f = 163.9 December 23, 1921.
μ = 0.570 25° C.
ρ = 1.872 Capillary 10.
$M/t = -0.000434 + 0.0000026482\ F$

Observation.	Shearing Stress, dynes per cm.^{2}	Efflux, g. per sec. Observed.	Efflux, g. per sec. Calculated.	Difference, per cent.
A*	1018	0.002361	0.002262	4.38*
	1017	0.002303	0.002259	1.95
	1017	0.002338	0.002259	3.50
	1017	0.002284	0.002259	1.11
B	1374	0.003311	0.003205	3.31
	1374	0.003213	0.003205	0.25
	1370	0.003117	0.003194	−2.47
	1356	0.003216	0.003157	1.87
	1372	0.003206	0.003199	0.22
	1371	0.003202	0.003197	0.16
C	1667	0.003977	0.003981	−0.10
	1667	0.003947	0.003981	−0.86
	1657	0.003867	0.003954	−2.25
	1656	0.003967	0.003951	0.41
D	1964	0.004727	0.004767	−0.85
	1979	0.004815	0.004807	0.17
	1978	0.004801	0.004804	−0.06
E	2361	0.005846	0.005818	0.48
	2353	0.005785	0.005797	−0.21
	2352	0.005796	0.005795	0.02
F	3107	0.007809	0.007794	0.19
	3106	0.007756	0.007791	−0.45
	3105	0.007830	0.007789	0.53
Average				0.78

All of the data obtained in the course of this investigation is published herewith with the following exceptions: (1) The data is condensed as indicated above, but it is hoped that its usefulness is not impaired thereby; (2) Sample 11 of Anti-rust Black gave values which were considerably different from the other samples supposed to be duplicates but as this sample was under suspicion of having lost vehicle during transit the data were rejected; (3) Sample 9 of Outside White *B* gave inconsistent results due to clogging. After again screening the paint, Table XXIII was obtained which is satisfactory;

TABLE XIX.—OUTSIDE WHITE A, SAMPLE 10.

$f = 380.6$ October 27, 1921.
$\mu = 0.3113$ 25° C.
$\rho = 1.948$ Capillary 11.
$M/t = -0.0051869 + 0.000013627\,F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC. OBSERVED.	EFFLUX, G. PER SEC. CALCULATED.	DIFFERENCE, PER CENT.
A	6489	0.08317	0.08324	−0.08
	6480	0.08340	0.08312	0.34
	6472	0.08346	0.08301	0.54
B	5964	0.07875	0.07608	3.51
	5958	0.07559	0.07600	−0.54
	5952	0.07619	0.07592	0.36
	5986	0.07634	0.07638	−0.52
C	5405	0.06900	0.06847	0.77
	5398	0.06815	0.06837	−0.32
D	4808	0.05986	0.06033	−0.78
	4803	0.05994	0.06026	−0.53
E	4110	0.04983	0.05082	−1.95
	4104	0.05010	0.05074	−1.26
F	3519	0.04328	0.04277	1.19
	3515	0.04207	0.04271	−1.50
	3510	0.04216	0.04264	−1.13
G	3164	0.03821	0.03793	0.74
	3160	0.03713	0.03787	−1.95
	3154	0.03783	0.03779	0.11
	3152	0.03775	0.03777	−0.05
H	2924	0.03546	0.03466	2.31
	2920	0.03514	0.03460	1.56
I	2595	0.03076	0.03018	1.92
	2591	0.03047	0.03012	1.16
J	2269	0.02603	0.02573	1.16
	2265	0.02522	0.02568	−1.79
*K**	1497	0.01692	0.01521	11.24*
	1493	0.01750	0.01516	15.44
*L**	955	0.01028	0.00783	31.10*
	952	0.01024	0.00779	31.50
Average				1.08

(4) The effects of shaking a paint with air and of evacuation are here investigated in merely a tentative manner, hence the data used in obtaining the equations of Tables XXXVII, XXXVIII, XXXIX and XL are omitted.

TABLE XX.—OUTSIDE WHITE A, SAMPLE 29.

$f = 166.4$ January 3, 1922.
$\mu = 0.2834$ 25° C.
$\rho = 1.947$ Capillary 11.
$M/t = -0.0020632 + 0.000012397\,F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC. OBSERVED.	EFFLUX, G. PER SEC. CALCULATED.	DIFFERENCE, PER CENT.
A	1713	0.01929	0.01917	0.59
	1707	0.01950	0.01910	2.10
B	2608	0.03054	0.03027	0.88
	2601	0.03016	0.03018	−0.73
C	3481	0.04038	0.04109	−1.75
	3494	0.04118	0.04125	−0.18
D	4406	0.05234	0.05256	−0.41
	4397	0.05201	0.05245	−0.84
E	5292	0.06448	0.06354	1.47
	5291	0.06355	0.06353	0.03
F	6478	0.07850	0.07825	0.33
	6500	0.07796	0.07852	−0.72
Average				0.84

TABLE XXI.—OUTSIDE WHITE A, SAMPLE A.

$f = 198.6$ January 23, 1922.
$\mu = 0.2926$ 25° C.
$\rho = 1.946$ Capillary 11.
$M/t = -0.0025409 + 0.000012794\,F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC. OBSERVED.	EFFLUX, G. PER SEC. CALCULATED.	DIFFERENCE, PER CENT.
(*A*)	1722	0.02005	0.01949	2.86)
	1718	0.02019	0.01944	3.84)
(*B*)	2260	0.02696	0.02637	2.21)
B	2255	0.02592	0.02631	−1.51
	2250	0.02636	0.02625	0.44
	2245	0.02608	0.02618	−0.39
C	1707	0.01951	0.01930	1.08
	1703	0.01950	0.01925	1.29
D	2963	0.03529	0.03537	−0.22
	2957	0.03530	0.03529	0.01
E	3918	0.04749	0.04759	−0.20
	3910	0.04740	0.04748	−0.18
F	4762	0.05842	0.05838	0.06
	4810	0.05889	0.05900	−0.19
G	5754	0.07120	0.07108	0.17
	5756	0.07124	0.07110	0.20
Average				0.46

TABLE XXII.—OUTSIDE WHITE B, SAMPLE 28.

$f = 430.1$ December 10, 1921.
$\mu = 0.2582$ 25° C.
$\rho = 2.002$ Capillary 11.
$M/t = -0.0049904 + 0.000011602\ F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC.		DIFFERENCE, PER CENT.
		OBSERVED.	CALCULATED.	
A	6568	0.07234	0.07121	1.59
	6557	0.07220	0.07108	1.58
B	5914	0.06448	0.06362	1.35
	5903	0.06365	0.06350	0.24
C	5295	0.05497	0.05644	−2.87
	5286	0.05619	0.05634	−0.27
	5277	0.05578	0.05623	−0.81
D	4580	0.04698	0.04815	−2.49
	4573	0.04839	0.04807	0.67
	4565	0.04790	0.04797	−0.15
E	3953	0.04072	0.04087	−0.37
	3945	0.04075	0.04078	−0.07
F	3170	0.03126	0.03179	−1.69
	3190	0.03203	0.03212	−0.28
	3214	0.03241	0.03230	0.34
G	2725	0.02665	0.02663	0.08
	2719	0.02687	0.02656	1.17
*H**	1839	0.01705	0.01635	7.95*
	1836	0.01724	0.01631	5.70
	1832	0.01685	0.01626	3.63
Average				0.93

TABLE XXIII.—OUTSIDE WHITE B, SAMPLE 9.

$f = 243.1$ January 4, 1922.
$\mu = 0.2331$ 25° C.
$\rho = 2.006$ Capillary 11.
$M/t = -0.0025441 + 0.000010504\ F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.^{2}	EFFLUX, G. PER SEC.		DIFFERENCE, PER CENT.
		OBSERVED.	CALCULATED.	
A	5772	0.05815	0.05809	0.10
	5761	0.05832	0.05797	0.59
B	4802	0.04783	0.04790	−0.48
	4780	0.04769	0.04767	0.05
C	3925	0.03862	0.03869	−0.17
	3918	0.03824	0.03861	−0.96
D	2977	0.02859	0.02873	−0.49
	2972	0.02844	0.02868	−0.82
E	2206	0.02060	0.02063	−0.13
	2202	0.02074	0.02059	0.74
F	1723	0.01560	0.01556	0.32
	1693	0.01538	0.01524	0.89
Average				0.46

TABLE XXIV.—OUTSIDE WHITE B, SAMPLE B.

f = 302.5 January 25, 1922.
μ = 0.2388 25° C.
ρ = 2.010 Capillary 11.
$M/t = -0.0032621 + 0.000010783\ F$

Observation.	Shearing Stress, dynes per cm.^{2}	Efflux, g. per sec. Observed.	Calculated.	Difference, per cent.
A	6513	0.06656	0.06697	−0.62
	6491	0.06660	0.06673	−0.20
B	5875	0.06086	0.06009	1.28
	5845	0.05973	0.05977	−0.05
C	4914	0.04987	0.04973	0.29
	4899	0.04942	0.04956	−0.29
D	4066	0.04039	0.04058	−0.47
	4059	0.03992	0.04051	−1.48
E	3090	0.03006	0.03006	0.00
	3085	0.02991	0.03000	−0.31
F	2472	0.02353	0.02339	0.57
	2455	0.02295	0.02321	−1.15
G	1696	0.01554	0.01503	3.45
	1694	0.01529	0.01500	1.89
Average				0.86

TABLE XXV.—OUTSIDE WHITE B, SAMPLE 28.

f = 239.7 January 31, 1922.
μ = 0.2263 25° C.
ρ = 2.002 Capillary 11.
$M/t = -0.0024395 + 0.000010178\ F$

Observation.	Shearing Stress, dynes per cm.^{2}	Efflux, g. per sec. Observed.	Calculated.	Difference per cent.
*A**	1822	0.01695	0.01611	5.25*
	1819	0.01701	0.01608	5.84
B	2456	0.02261	0.02256	0.23
	2445	0.02255	0.02245	0.46
C	3162	0.02976	0.02974	0.05
	3157	0.02994	0.02969	0.82
D	3909	0.03693	0.03735	−1.13
	3941	0.03770	0.03767	0.06
E	4839	0.04637	0.04681	−0.96
	4831	0.04676	0.04673	0.05
F	5610	0.05461	0.05466	−0.09
	5629	0.05530	0.05486	0.81
Average				0.47

Table XXVI.—Mill White Gloss A, Sample 12.

$f = 318.6$ October 31, 1921.
$\mu = 0.1904$ 25° C.
$\rho = 1.709$ Capillary 11.
$M/t = -0.0023305 + 0.0000073091\ F$

Observation.	Shearing Stress, dynes per cm.²	Efflux, g. per sec.		Difference per cent.
		Observed.	Calculated.	
A	6702	0.04664	0.04665	−0.02
	6697	0.04697	0.04662	0.75
B	6254	0.04364	0.04338	0.60
	6250	0.04348	0.04335	0.30
C	5951	0.04172	0.04117	1.33
	5947	0.04144	0.04114	0.73
D	5403	0.03690	0.03716	−0.70
	5400	0.03709	0.03714	−0.13
E	4815	0.03290	0.03286	0.12
	4811	0.03273	0.03284	−0.34
F	4088	0.02775	0.02755	0.72
	4085	0.02757	0.02753	0.15
G	3502	0.02315	0.02327	−0.52
	3493	0.02255	0.02320	−2.88
	3495	0.02287	0.02321	−1.49
H	2852	0.01843	0.01852	−0.49
	2849	0.01843	0.01849	−0.32
I	2238	0.01385	0.01403	−1.30
Average				0.72

Table XXVII—Mill White Gloss A, Sample 31.

$f = 366.6$ December 12, 1921.
$\mu = 0.1897$ 25° C.
$\rho = 1.709$ Capillary 11.
$M/t = -0.002656 + 0.0000072455\ F$

Observation.	Shearing Stress, dynes per cm.²	Efflux, g. per sec.		Difference, per cent.
		Observed.	Calculated.	
A	1833	0.01085	0.01063	2.07
	1831	0.01078	0.01061	1.60
B	2702	0.01692	0.01692	0.00
	2698	0.01674	0.01689	−0.90
C	3541	0.02288	0.02300	−0.52
	3535	0.02283	0.02296	−0.57
D	4383	0.02913	0.02910	0.10
	4403	0.02919	0.02925	−0.21
E	5265	0.03554	0.03549	0.14
	5258	0.03556	0.03544	0.34
F	6079	0.04146	0.04139	0.17
	6097	0.04131	0.04152	—0.51
Average				0.59

DATA.

Thirteen different paints were made up as a set of 52 samples (4 samples of each paint) under the supervision of Dr. James E. Booge of the E. I. du Pont de Nemours and Co. and were sent to the Gayley Laboratory, Lafayette College, for determination of the plasticity values of as many samples as seemed desirable. These determinations were made without knowledge of the kind of paint, its formula, or its duplicate or triplicate samples. In this way, all results were unprejudiced. All samples were treated as nearly alike as possible in the mixing, sieving, time of standing in the water bath, etc.

TABLE XXVIII.—BLACK ENAMEL A, SAMPLE 14.

$f = 158.2$ November 10, 1921.
$\mu = 0.5877$ 25° C.
$\rho = 0.898$ Capillary 10.
$M/t = -0.00020729 + 0.0000013106\, F$

Observation.	Shearing Stress, dynes per cm.²	Efflux, g. per sec. Observed.	Efflux, g. per sec. Calculated.	Difference, per cent.
*A**	714	0.000763	0.000728	4.80*
	713	0.000800	0.000727	10.00
*B**	1054	0.001218	0.001174	3.75*
	1054	0.001221	0.001174	4.00
C	1491	0.001740	0.001747	−0.40
	1491	0.001704	0.001747	−2.52
D	1666	0.001966	0.001976	−0.51
	1666	0.001997	0.001976	1.06
E	1944	0.002352	0.002341	0.47
	1943	0.002342	0.002339	0.13
F	2291	0.002821	0.002795	0.93
	2290	0.002804	0.002793	0.39
G	2571	0.003185	0.003162	0.73
	2570	0.003118	0.003161	−1.38
H	2991	0.003708	0.003713	−0.13
	2984	0.003669	0.003704	−0.95
I	3136	0.003954	0.003903	1.31
	3135	0.003900	0.003901	−0.03
Average				0.78

In Tables IV to XXXIII there are presented all the data on 29 samples of paint observed during the course of our investigation. Shearing stress at the wall of the tube is designated by F and is expressed in dynes per square centimeter. Efflux or weight of flow is M/t expressed in grams per second, μ is the mobility, f the yield value,[1] and ρ the density of the paint. The date given with each individual sample is the date on which that determination was made. The constant temperature bath was in all cases set at 25° C. The straight line equation with M/t and F as variables is that equation derived from the observed data by the method of averages.[2] By this equation are given the calculated values listed in column 4.

Table XXIX.—Black Enamel A, Sample 7.

$f = 236.3$ October 8, 1921.
$\mu = 0.627$ 25° C.
$\rho = 0.898$ Capillary 12.
$M/t = -0.0029690 + 0.000012564\ F$

Observation.	Shearing Stress, dynes per cm.²	Efflux, g. per sec.		Difference, per cent.
		Observed.	Calculated.	
A	1578	0.01678	0.01686	−0.48
	1574	0.01672	0.01681	−0.54
	1568	0.01678	0.01673	0.30
B	1397	0.01476	0.01458	1.23
	1394	0.01474	0.01455	1.31
*C**	896	0.00961	0.00829	15.98*
	894	0.00931	0.00826	12.71
	891	0.00941	0.00823	14.34
*D**	556	0.00549	0.00402	36.57*
	553	0.00550	0.00398	38.19
E	3121	0.03610	0.03624	−0.39
	3118	0.03610	0.03621	−0.30
F	3767	0.04420	0.04436	−0.36
	3764	0.04410	0.04432	−0.50
G	4001	0.04750	0.04730	0.42
	3998	0.04670	0.04726	−1.19
H	2123	0.02414	0.02370	1.86
	2121	0.02400	0.02368	1.35
Average				0.79

It may be observed in many of the tables that the variation from the straight line increases greatly at very low pressures. The relation between pressure and weight of flow is no longer linear and the points experimentally determined at these low pressures slope off gradually towards the origin. The curves for Samples 25, 7 and 2, given in Fig. 2, may be taken as typical. The exact cause of this increased flow at low pressures is still an open question, but it is most pronounced in the capillaries of largest diameter. It may be due to seepage[1] of the vehicle through the interstices of the pigment particles, or due to an incomplete establishment of the shear conditions throughout the entire diameter of the capillary.[2]

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[1] The yield value is obtained by extrapolating the flow-shearing stress curves and it is independent of the dimensions of the capillary or of any assumptions as to the nature of the flow within the capillary. An investigation has been begun which may yield some useful knowledge in regard to the nature of flow using the falling-sphere and capillary-tube method. To bring about agreement between the different methods, it may be found desirable to multiply the yield value obtained here by some simple factor as, for example, 0.75. See Bingham's "Fluidity and Plasticity," p. 225.

[2] Lipka, "Graphical and Mechanical Computation," p. 127.

TABLE XXX.—WHITE ENAMEL A, SAMPLE 16.

$f = 425.1$ November 15, 1921.
$\mu = 0.054$ 25° C.
$\rho = 1.503$ Capillary 11.
$M/t = -0.00077593 + 0.0000018252\ F$

Observation.	Shearing Stress, dynes per cm.²	Efflux, g. per sec. Observed.	Calculated.	Difference, per cent.
A	6554	0.01103	0.01119	−1.44
	6552	0.01116	0.01118	−0.20
B	6242	0.01052	0.01062	−0.96
	6239	0.01052	0.01061	−0.83
C	5649	0.009737	0.009535	2.12
	5634	0.009452	0.009507	−0.58
	5644	0.009734	0.009526	2.18
D	5061	0.008478	0.008462	0.18
	5046	0.008386	0.008434	−0.57
E	4062	0.006618	0.006638	−0.30
	4047	0.006538	0.006611	−1.12
F	3496	0.005563	0.005605	−0.75
	3494	0.005564	0.005601	−0.66
G	2865	0.004510	0.004453	1.28
	2864	0.004470	0.004452	0.40
H	2256	0.003427	0.003342	2.54
	2255	0.003400	0.003340	1.80
*I**	1506	0.002176	0.001973	10.29*
	1505	0.002156	0.001971	9.39
Average				1.05

The best course of procedure seemed to be to avoid using values at so low a rate of efflux that they fail to lie on a straight line. We have, therefore, discarded the values denoted by an asterisk in getting our equation for the straight line curve.

In columns 3 and 4 of Tables IV to XXXIII, are listed values of efflux, observed and calculated. The observed values were obtained by actual timing and weighing.

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[1] U. S. Bureau of Standards, *Bulletin No. 278*, p. 332.

[2] E. Buckingham, "On Plastic Flow Through Capillary Tubes," *Proceedings*, Am. Soc. Test. Mats., Vol. 21, p. 1154 (1921).

TABLE XXXI.—WHITE ENAMEL A, SAMPLE 34.

$f = 355.1$ December 20, 1921.
$\mu = 0.0563$ 25° C.
$\rho = 1.503$ Capillary 11.
$M/t = -0.00063701 + 0.0000017939\ F$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.²	EFFLUX, G. PER SEC.		DIFFERENCE, PER CENT.
		OBSERVED.	CALCULATED.	
A	2475	0.003798	0.003803	−0.13
	2480	0.003848	0.003812	0.94
B	3214	0.005153	0.005129	0.47
	3212	0.005122	0.005125	−0.06
C	3944	0.006430	0.006438	−0.12
	3942	0.006394	0.006435	−0.64
D	4647	0.007695	0.007699	−0.05
	4645	0.007706	0.007696	0.13
E	5290	0.008831	0.008853	−0.25
	5287	0.008826	0.008847	−0.24
F	5899	0.009871	0.009945	−0.75
	5895	0.009925	0.009938	−0.13
G	6580	0.011259	0.011167	0.82
	6562	0.011164	0.011135	0.26
Average				0.36

TABLE XXXII.—ANTI-RUST RED A, SAMPLE 13.

$f = 88.0$ November 2, 1921.
$\mu = 0.7954$ 25° C.
$\rho = 1.265$ Capillary 10.
$M/t = -0.00021961 + 0.0000024970\ F.$

OBSERVATION.	SHEARING STRESS, DYNES PER CM.²	EFFLUX, G. PER SEC.		DIFFERENCE, PER CENT.
		OBSERVED.	CALCULATED.	
F	1214	0.00276	0.002812	−1.88
	1213	0.00277	0.002809	−1.41
G	1670	0.00394	0.003950	−0.25
	1669	0.00393	0.003948	−0.46
H	2275	0.00558	0.005461	2.18
	2275	0.00545	0.005461	−0.20
I	2696	0.00652	0.006512	0.18
	2692	0.00649	00.06502	−0.23
J	2988	0.00728	0.007241	0.48
	2988	0.00722	0.007241	−0.28
Average				0.76

TABLE XXXIII.—ANTI-RUST RED A, SAMPLE 32.

$f = 89.0$ December 13, 1921.
$\mu = 0.8215$ 25° C.
$\rho = 1.260$ Capillary 10.
$M/t = -0.00022861 + 0.0000025691\ F.$

OBSERVATION.	SHEARING STRESS, DYNES PER CM²	EFFLUX, G. PER SEC.		DIFFERENCE, PER CENT.
		OBSERVED.	CALCULATED.	
A	3198	0.007908	0.007987	−1.00
	3197	0.007916	0.007985	−0.87
B	2796	0.007044	0.006955	1.28
	2795	0.006974	0.006952	0.32
C	2401	0.005977	0.005940	0.62
	2394	0.005887	0.005922	−0.59
	2393	0.005940	0.005919	0.35
D	1983	0.004877	0.004866	0.23
	1983	0.004872	0.004866	0.12
E	1518	0.003701	0.003671	0.82
	1517	0.003638	0.003669	−0.85
Average				0.64

The equation obtained by the method of averages is the typical slope-intercept form of the straight line:

$$M/t = a + bF \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

M/t is the weight of flow in grams per second; F is the shearing stress in dynes per square centimeter. The constants have significance as shown in this form:

$$M/t = -\frac{\mu\pi R^3 f\rho}{4} + \frac{\mu\pi R^3\rho}{4}F \ldots\ldots\ldots\ldots (2)$$[1]

or

$$M/t = \frac{\mu\pi\rho R^3}{4}(F-f) \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where μ = mobility, f = yield value, ρ = density of the paint, and R the radius of the capillary. The mobility may be obtained from Eq. 3.

The yield value may be obtained either by graph or by the formula:

$$f = \frac{F_2M_1/t_1 - F_1M_2/t_2}{M_1/t_1 - M_2/t_2} \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where M_1/t_1 is the weight of flow in grams per second at the shear F_1 dynes per square centimeter, etc.

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[1] For the derivation of this equation, see Bingham's "Fluidity and Plasticity," p. 225.

Shearing stress bears the relationship to the pressure:

$$\pi R^2P = -2\pi rlF \text{ or } F = -RP/2\,l,$$

where R and l are, respectively, the radius and the length of the capillary. The gravity constant at Easton, Pa., is 980.6 dynes and this value was used in transforming the pressure to shear in dynes.

The dimensions of the capillary tubes used in this investigation were carefully determined by W. R. Bender and are as tabulated:

Table XXXIV.—Dimensions of Capillaries.

Capillary.	No. 10.	No. 11.	No. 12.	No. 13.
Length, cm	3.051	3.041	4.998	5.018
Radius, by mercury, cm	0.01469	0.03062	0.03053	0.01458
Average minor radius, cm	0.01398	0.02971	0.02932	0.01385
Average major radius, cm	0.01547	0.03210	0.03180	0.01534
Radius, calculated, for use, cm	0.01467	0.03058	0.03051	0.01456

Neglecting those points which slope off towards the origin at very low pressures and, also, those which were in error for known reasons, the average variation from the straight line equation determined algebraically, was 0.69 per cent. The extreme limits of variation for the 40 samples examined were 0.26 per cent (Table XII) and 1.28 per cent (Table XVI).

Plastometer determinations were started on these paints in September, 1921, and carried through until February, 1922. As the work progressed, our technique gradually improved. Comparison of the average variation with the date of determination shows that the deviation for the first half of the paints was 0.85 per cent and for the last half, 0.53 per cent. The inference from this is that, using the method as it now stands, an average deviation from a true straight line of about 0.5 per cent, rather than as high a percentage as our 0.7 per cent, could be expected by an operator with some previous knowledge of the theory and experience with the apparatus.

The maximum error for density determination was 0.2 per cent. This error, high for a specific gravity determination, was caused by the presence throughout the paint of minute air bubbles which could not be removed without removing volatile thinners. Weighings were made to 0.1 mg. Pressures were read from the manometer to 0.1 cm., an error of 0.009 to 0.5 per cent, the average error of all our readings being 0.16 per cent. Temperatures were controlled by an electric thermostat to 25° C. with a maximum change of 0.003° C., indicated by a Beckmann thermometer. The source of largest consistent error lay in the measurement of the time. The time of efflux was recorded on a Swiss "Surburban" stop watch corrected by a factor of 0.9985. Assuming a probable error of 0.3 sec., the percentage of error ranged from 0.14 to 0.6 per cent, averaging approximately 0.25 per cent. To illustrate the effect of watch error, we have divided all our points into groups depending upon the number of seconds given to each determination, and in the next table the average variation for the three groups are compared.

TABLE XXXV.

SECONDS OF FLOW.	AVERAGE VARIATION OF OBSERVED POINTS.
50 to 100 sec.	0.88 per cent
100 to 150 "	0.66 "
150 to 300 "	0.60 "

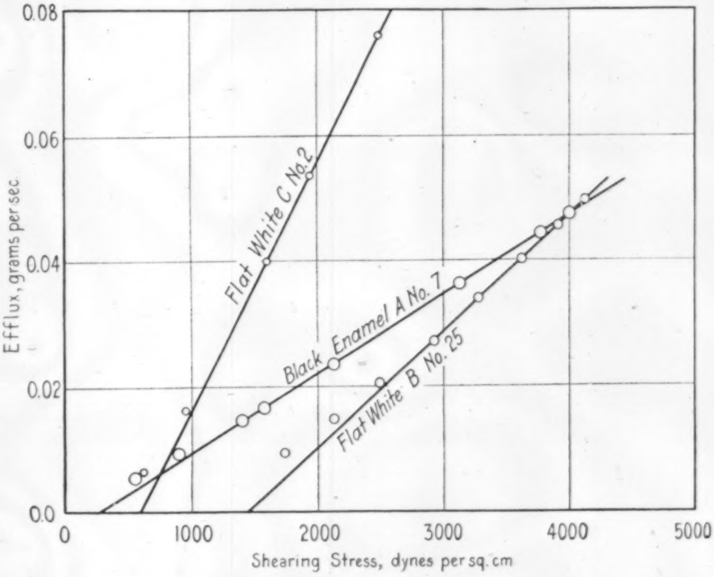

FIG. 2.—Relation between Efflux and Shearing Stress.

The fact, shown by these figures, that the accuracy increases with increasing time of flow, is another strong argument for the use of a fine capillary, with which the flow will be relatively slow and the trouble and time of refilling the plastometer-container will be reduced to a minimum.

Whereas the slow capillary is to be preferred, the diameter has its lower limit, depending presumably on the size and nature of the pigment particles. As an example, the case of Paint No. 29 is cited.

The paint was well stirred as usual and was rubbed through the 300-mesh gauze. A small amount of the coarser filler would not pass through and was screened off. The very fine capillary, No. 10, was used. Although the tube was never totally plugged, the flow was very irregular and the observed points fell on no very definite curve.

TABLE XXXVI.—YIELD VALUES AND MOBILITIES OF PAINT SAMPLES AS OBTAINED BY BOTH THE GRAPHICAL AND ALGEBRAIC METHODS.

Paint No.	Paint.	Sample No.	Graphical.		Algebraic.		Density.
			Yield Value.	Mobility.	Yield Value.	Mobility.	
1	Flat White *C*	24	585	1.235	551.2	1.223	1.663
		2	580	1.072	591.4	1.076	1.660
2	Flat White *A*	26	705	0.656	711.1	0.661	1.706
		1	870	0.651	860.0	0.650	1.704
		39	690	0.638	704.4	0.640	1.708
3	Flat White *B*	27[a]	1245	0.412	1247.4	0.409	1.736
		25	1410	0.470	1443.6	0.478	1.738
		8	1280	0.422	1302.0	0.426	1.735
4	Outside White *C*	37	190	0.586	163.9	0.582	1.869
		3	190	0.578	174.4	0.570	1.872
5	Outside White *A*	10	370	0.310	380.6	0.311	1.948
		29[b]	120	0.282	166.4	0.283	1.947
		A	200	0.293	198.6	0.293	1.946
6	Outside White *B*	9[c]	60	0.234	88.3	0.236	2.011
		28	520	0.265	430.1	0.258	2.000
		9	240	0.236	243.1	0.233	2.006
		B	260	0.236	302.5	0.239	2.009
		28	250	0.227	239.7	0.226	2.002
7	Anti-rust Black *C*	4	330	1.616	345.8	1.621	1.101
		36	320	1.633	332.4	1.647	1.100
8	Anti-rust Black *A*	11[c]	320	0.910	306.6	0.903	1.120
		30	300	1.049	307.0	1.052	1.097
9	Anti-rust Black *B*	5	360	0.795	372.7	0.799	1.185
		18	360	0.796	314.5	0.783	1.183
10	Mill White Gloss *A*	12	345	0.197	318.6	0.190	1.709
		31	350	0.188	363.0	0.187	1.709
11	White Enamel *A*	16	440	0.055	425.0	0.054	1.503
		34	360	0.053	355.1	0.056	1.503
12	Black Enamel *A*	14	200	0.600	158.2	0.588	0.898
		7	220	0.621	236.3	0.627	0.898
13	Anti-rust Red *A*	13	105	0.804	90.7	0.797	1.265
		32	100	0.826	106.2	0.831	1.260

[a] See p. 30. [b] See pp. 28 and 29. [c] See pp. 16, 17 and 30.

A check determination with Capillary No. 10 was performed and similar inconsistent results were obtained. A coarser capillary, No. 11, was then used on Sample 29, and a very good curve was established. It is curious to note that the values of efflux with the fine capillary, No. 10, were high. We would expect them to be low if at all different from normal.

The above table compares the plasticity values ascertained by the graphical method, plotting shearing stress against weight of flow with those given by the algebraic method of averages. The algebraic method is doubtless the more accurate, but the graphical method is also useful. Their comparison is of interest.

The difference between plasticity values for duplicates is often considerable, as between Samples Nos. 25 and 27, both "Flat White *B*." Such differences are certainly not due to error in measurement, but the values represent with fair accuracy the consistency of each respective paint as it existed within the plastometer at the time of observation, though a previous difference in treatment is possible. This conclusion is necessary inasmuch as the observed points for each individual paint fall upon their theoretical straight line with a percentage variation which is quite small as compared with the variation between the two curves of the duplicate samples. Thus, the yield values of Samples No. 25 and No. 27 differ from their mean by 7.29 per cent, their mobilities by 7.78 per cent. The average variation of the observed points from the calculated is 1.05 per cent for Sample No. 27, and 0.63 per cent for Sample No. 25.

There are many plausible explanations for a difference between duplicate samples, any one or all of which may have a bearing upon the results. It is common knowledge among paint men that, upon standing, a paint will change, although the nature of this change, whether chemical or physical, is in dispute. And it is claimed that two samples from one batch of paint will change unequally. Our investigation covered a period of about five months, during which time all samples were standing in quart cans tightly covered at laboratory temperature. When the determinations were made it was not known which paints were duplicates and often several weeks elapsed between the two, as shown by the dates in the tables. This, however, is hardly the cause of the above discrepancy since Sample No. 25 was measured on November 22 and Sample No. 27 on November 25. From some cans, a leakage of oil had taken place during the period of transportation from the factory to our laboratory. Where this leakage was evident, the samples were discarded. But on some samples that were used, enough clear oil had issued from the can to form a small rim of hardened oil around the lid. A small amount had issued from cans Nos. 5, 9, 10, 14, 18, 28, 29, 31. A larger incrustation of oxidized oil was found on cans Nos. 3, 4, 11, 36, *A*, *B*. From the others, no leakage had occurred. As an example of the effect of leakage, this could easily be the cause of a difference between Sample No. 11 and No. 30, the loss in vehicle lowering the mobility from 1.052 to 0.903. The difference between their specific gravities, 1.120 for Sample No. 11, and 1.097 for Sample No. 30, seems to substantiate this possibility. Their yield values are the same, 306.6 for Sample No. 11 and 307.0 for Sample No. 30. Due to the suspicion resting on Sample No. 11, its values have been excluded.

In preparing the paints for the plastometer, an effort was always made to give the same treatment to each one. However, in the stirring a factor of personal judgment entered. The paints were undoubtedly homogeneous as a whole when finally used, but in shaking and mixing, more or less air was unavoidably beaten in. This air emulsion would obviously have an effect upon the consistency. An inquiry into just what the effect is, was made by running several samples before and after vigorously shaking to incorporate as much of an air emulsion into the paint as possible.

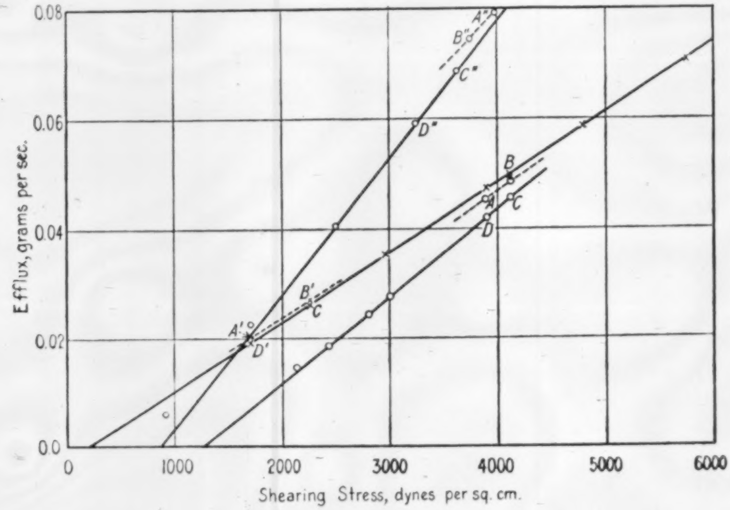

FIG. 3.—Relation between **Efflux** and **Shearing Stress of Paint Run through a Fine Screen.**

In the cases of Samples Nos. 28 and 39, both the mobility and yield value were increased slightly by shaking in air. In the case of the very thick Paint No. 25, shaking seemed to have the opposite effect. The cause for the different behavior is not clear.

An attempt was made to bring the consistency back to its original value by evacuating the air bubbles from the sample shaken with air. The result was unsatisfactory because much volatile thinner was lost. The plasticity values of Paint No. 25 were thus changed enormously, as given in Table XL.

In a few instances, it has been observed that a paint, being run in the plastometer soon after it had been passed through the fine screen, gave a greater flow than it did after standing for a couple of hours. A possible explanation seems to be that there exists within the paint some colloidal matter which is broken up by the 300-mesh screen, but which resets on standing. In Fig. 3 are plotted three such cases.

TABLE XXXVII.—STUDY OF THE POSSIBLE EFFECT OF THOROUGH SHAKING IN AIR UPON THE CONSTANTS OF A PAINT. OUTSIDE WHITE B, SAMPLE 28. (SHAKEN WITH AIR.)

$f = 254.2$ February 1, 1922.
$\mu = 0.2477$ 25° C.
$\rho = 2.000$ Capillary 11.

$$M/t = -0.0028292 + 0.000011131\ F.$$

TABLE XXXVIII.—FLAT WHITE A, SAMPLE 39. (SHAKEN WITH AIR.)

$f = 879.5$ January 7, 1922.
$\mu = 0.6565$ 25° C.
$\rho = 1.702$ Capillary 11.

$$M/t = -0.022088 + 0.000025114\ F.$$

TABLE XXXIX.—FLAT WHITE B, SAMPLE 25. (SHAKEN WITH AIR.)

$f = 1249.7$ November 28, 1921.
$\mu = 0.3641$ 25° C.
$\rho = 1.736$ Capillary 12.

$$M/t = -0.017619 + 0.000014098\ F.$$

TABLE XL.—THE EFFECT OF SUBJECTING PAINT TO DIMINISHED PRESSURE AFTER SHAKING. FLAT WHITE B, SAMPLE 25. (EVACUATED.)

$f = 2060.7$ November 29, 1921.
$\mu = 0.400$ 25° C.
$\rho = 1.740$ Capillary 11.

$$M/t = -0.03217 + 0.000015611\ F.$$

The high values, A and B, were first observed. The flow then suddenly fell to C, and higher values than the curve DF could not again be obtained. The gel formation, by this explanation, occurred between points B and C.

The samples in which this was observed most clearly were Nos. 1 and 27, and Outside White A. The first two were of a "Flat White" series to which a little emulsifying agent had been added for the purpose of producing an "artificial body." In the formula of the "Outside White" a small amount of different emulsifying agent is found. These substances are probably in the paint in a colloidal state and could cause the variation in consistency that we have observed. In the other classes of paints, no such colloids were present.

The Paints *A*, *B*, and *C*, of each of the series: Flat White, Outside White, and Anti-rust Black, differ from each other only by varying the proportions of vehicle. The effect of thinning may readily be seen from Table XLI. The mobility is increased and the yield value decreased. Oil added to Flat White *B* to make Flat White *A* increased μ from 0.438 to 0.650 and lowered f from 1331 to 758. On further dilution, changing Paint *A* to Paint *C*, μ went from 0.650 to 1.150, and f from 758 to 571.

TABLE XLI.—CORRELATION BETWEEN CONSISTENCY TESTS AND PLASTICITY VALUES.

Paint No.	Paint.	Average Consistency.	Average Yield Value.	Average Mobility.	$\frac{f}{\mu}$	Shearing Stress in dynes per cm² where Curvature Begins.	Shearing Stress in Excess of Yield Value where Curvature Begins.
1	Flat White *C*	−0.26	571	1.150	497	1650	1080
2	Flat White *A*	0.36	758	0.6503	1166	1730	970
3	Flat White *B*	2.24	1331	0.4377	3040	2450	1120
4	Outside White *C*	−0.80	169	0.576	294	1250	1080
5	Outside White *A*	0.0	248	0.2957	840	1550	1300
6	Outside White *B*	0.5	260	0.2384	1092	1680	1380
7	Anti-rust Black *C*	−0.80	339	1.634	2075	1200	860
8	Anti-rust Black *A*	0.20	307	1.052	292	1520	1210
9	Anti-rust Black *B*	0.14	344	0.791	434	2100	1760
10	Mill White *A*	1.20	341	0.1885	1807	1900	1560
11	White Enamel *A*	1.46	390	0.055	7091	3000	2610
12	Black Enamel *A*	−0.26	198	0.6075	324	1450	1250
13	Anti-rust Red *A*	−0.66	98	0.814	121	1350	1250
						Average	1340

CONCLUSIONS.

BY EUGENE C. BINGHAM.

The definiteness of the existence of two properties which we have called friction (or yield value) and mobility seems now established by the confirmation of several workers using a variety of materials and conditions of flow. There is still a difference of opinion as to the character of the flow at small shearing stresses and there is a dearth of material available to show what correlation, if any, exists between the new properties and the better known properties of consistency, hardness, etc. Specifically, the paint manufacturer has become familiar with the term "painting consistency," which is measured in a variety of ways, but the questions arise: Can this property be accurately measured and would different laboratories agree in their measurements? Is it related to the yield value alone, the mobility alone, or to both? Is it possible to specify certain limits within which the yield value and the mobility of a paint must fall in order to be suitable for use? Is the measurement of plasticity accurate and practicable? Does the plasticity of a paint remain constant through a period of weeks or months after it has been prepared? Just what parts do fineness of grain, fluidity of vehicle, the presence of colloids or hydrogen ions have upon the plasticity of a paint, and why is it that the same pigment ground in different oils should require very different volumes of oil?

At the suggestion of P. H. Walker we have planned a cooperative investigation to answer some of these questions.

This investigation enables us to reach the following conclusions:

1. The ordinary methods of testing consistency, although rough, do lead to a pronounced correlation. The lack of complete correlation is partly due to the fact that the methods used and the standards aimed at by the committee were not the same.

2. The plasticity method gives us a more delicate method for identifying a paint than any in use, the average deviation between the observed and calculated values being about 0.7 per cent. Having two properties which are independent variables, it becomes possible to identify positively several hundred paints, all of painting consistency, provided that a method can be worked out for preparing the samples for the plastometer which will maintain the identity of each sample.

3. The plasticity method proves that some of the paints made up as duplicates were in fact different. The pint cans were filled from the same larger paint sample which had been thoroughly mixed, consequently initially there could not have been any difference. Any difference which developed must have been due to changes in consistency on standing or possibly to leakage. Any trace of oil around the run of the can was sufficient cause for comment and where possible avoiding the sample altogether. This makes it necessary in the future to take additional precautions in the preparation of a series of paints to see that the past history of the paints at the time of measurement is more nearly the same, if perfectly consistent results are to be obtained. Our plastometer measurements are at present far superior to our method for preparing the sample for the plastometer. The possible change of structure by stirring, sieving, change of temperature, or simple standing, the loss of volatile thinner, the effect of very small amounts of moisture, the screening off of coarse particles, or the effect of coarse particles on the flow, as well as the

presence of variable amounts of emulsified air in the material must be taken more carefully into account in subsequent studies.

4. A considerable mass of data is presented herewith which shows that the efflux-shear curve is linear after the flow is established. This conclusion seems to set at rest any fears as to the definiteness of the yield value as extrapolated so far as this class of material is concerned. Before the flow is fully established, the curve is not linear. This confirms earlier observations. The data afford further evidence that the yield value and mobility of a given paint are independent of the dimensions of the particular capillary used. See Bingham's "Fluidity and Plasticity," p. 219.

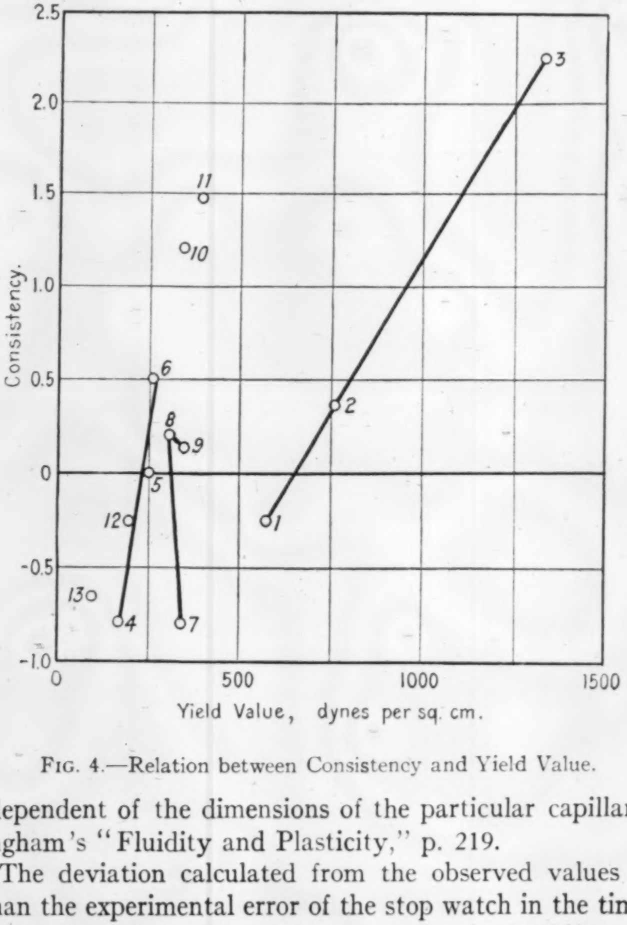

FIG. 4.—Relation between Consistency and Yield Value.

5. The deviation calculated from the observed values is little more than the experimental error of the stop watch in the time intervals employed, so that greater accuracy can be obtained if one chooses to spend the additional time; but for the present any additional time would be better spent in more careful preparation of the sample for the plastometer.

6. There is no very simple, mathematical relationship between the mean estimate of the paint experts and the measured yield and mobility values. But, it would be very surprising if such a relationship did appear. There is, however, complete correlation between the two sets of figures, except in one case. Paint No. 1, Flat White *C*, was judged too thin in consistency, because of the very high mobility revealed by the plastometer. Paint No. 3, Flat White *B*, was too thick because of a very high yield value. Paint No. 4, Outside White *C*, was very thin because of a low yield value. Paint No. 6, Outside White *B*, was a little too thick because of a rather low mobility. Paint No. 7, Anti-rust Black *C*, was very thin due to an extremely high mobility. Paint No. 8, Anti-rust Black *A*, was estimated to be a little thicker than Paint No. 9, Anti-rust Black *B*, an error in judgment as shown by the plastometer results. Paint No. 10, Mill White Gloss *A*, was very thick because of its very low mobility. Paint No. 11, White Enamel *A*, contained a large percentage of varnish which gave it an abnormally low mobility, although there is nothing about the consistency which would mark off this paint as being peculiar. Paint No. 12, Black Enamel *A*, and Paint No. 13, Anti-rust Red *A*, were thin due to low yield values. From this it is evident that painting consistency is not dependent upon any one value but that the yield value and mobility play an equally important part. For a paint of best consistency the yield value must be high if the mobility is low, or *vice versa*. Addition of pigment increases the yield value and the mobility is greatly lowered by addition of varnish, as we have seen in the case of Paint No. 11, White Enamel *A*. Thinning with oil increases the mobility and generally lowers the yield value. Yield value and mobility probably have their limits depending upon such properties as the manual difficulty in spreading, the appearance of brush lines, or slipping from a vertical surface. What these limits are can only be determined by the gradual accumulation of plasticity data.

7. If we compare the consistencies with the yield values as is done graphically in Fig. 4, we can see that there is ordinarily only a slight increase in yield value as one goes from paints which are too thin to those that are distinctly too thick. The yield value varies only within fairly narrow limits, namely between 100 and 400 dynes per cm^2, except in the case of the flat white Paints Nos. 1, 2, and 3, the last having the extraordinarily high yield value of 1331. These paints are the only ones studied which contain a considerable amount of emulsifying agent, Paint No. 2 containing less than Paint No. 3 and Paint No. 1 less than either. The amount of pigment in Paint No. 3 is 66.31 per cent, which is not essentially

different from Paint No. 6 which contains 65.15 per cent but, of course, this is weight per cent, which is not very significant. Nevertheless, we are probably justified in attributing the high yield value of the flat white paints to the emulsifying agent, and as thinner is added, the yield value is lowered in a linear manner. This same lowering of the yield value on adding thinner is shown by the Series 6, 5, and 4. In the series 9, 8, and 7, Paint No. 8 was given a consistency which is practically identical with that given Paint No. 9.

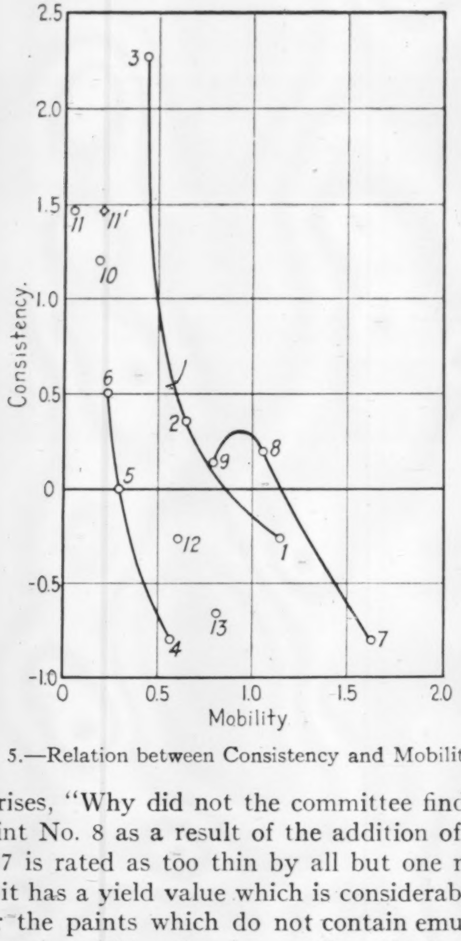

FIG. 5.—Relation between Consistency and Mobility.

The question arises, "Why did not the committee find a lower consistency for Paint No. 8 as a result of the addition of thinner?"

Paint No. 7 is rated as too thin by all but one member of the committee, yet it has a yield value which is considerably higher than the average for the paints which do not contain emulsifying agent. This shows that the yield value is not the only factor controlling plasticity and brings us naturally to a consideration of the importance of the mobility.

8. When we compare the mobilities of paints with the consistencies as shown in Fig. 5 we must continually keep in mind the results of our study of the yield value, because consistency is of course a composite property. We see now that the thinness of Paint No. 7 is explained by the high *mobility* of this paint. On the other hand, Paint No. 10, which has the same yield value as Paint No. 7, is nevertheless too thick because of too low a mobility. Paint No. 11 has a still higher consistency because it has a slightly higher yield value than Paint No. 10 and at the same time a considerably lower mobility.

On the other hand, Paint No. 1, with a very high yield value, is still a little too thin, due to a very high mobility. It is evident that the emulsifying agent affects the yield value very greatly without influencing the mobility very much.

Dilution of paints with thinner causes the mobility to be increased and, therefore, it rapidly lowers the consistency. However, a change in mobility is far more effective in thick paints than in thin ones, as is shown by the curvature of the curves in Fig. 5 for the series 3, 2, and 1 and 6, 5 and 4. The series 9, 8, and 7 is again exceptional in that Paint No. 9 should have been rated with a consistency of 1.2 instead of 0.14 to conform with the other paints.

9. Dr. Edward W. Washburn in his "Physical Chemistry" has defined the plasticity of a solid as the product of the yield value multiplied by the mobility. But this is a special definition of plasticity which we are unwilling to adopt. Steel has a high yield value and a low mobility and paint has a low yield value and a high mobility. If in a given case the products of the two independent variables happened to be the same for two materials, it is difficult to see any significance. It seems to us much better to treat these variables as being quite separate. As we accumulate more data, we may find it feasible to specify maximum and minimum values for both the yield value and the mobility for different classes of materials.

It is obvious from what has gone before that as the yield value of a paint increases, it is possible at the same time to increase the mobility within certain limits and obtain a satisfactory plasticity; thus, it would seem as though the ratio of yield value to mobility might have a certain minor usefulness. This ratio f/μ is plotted against the consistency in Fig. 6 and it is seen that most of the paints lie fairly close to a smooth curve. Paint No. 11 is highly exceptional in this regard, this being an enamel containing a vehicle with exceptionally low fluidity. Had the mobility been only as high as 0.2 indicated by the point 11′ in Fig 5, this paint would have fallen on the curve in Fig. 6.

10. The paints studied are too complicated in composition to permit our drawing many conclusions in regard to the effect of fineness of grain or chemical composition on the plasticity constants. There is the widest difference in the percentages of pigments, ranging from 3.12 per cent for Paint No. 12 to 65.15 per cent for Paint No. 6 and 66.31 per cent for Paint No. 3. But alkaline substances are present in the paints having the higher percentages of pigment which tends to lower the yield value and raise the mobility. The fluidity of the vehicle doubtless plays an important part in controlling the mobility of the paint, as, for example, Paint No. 12 which with its low percentage of pigment contains a vehicle high in varnish gums.

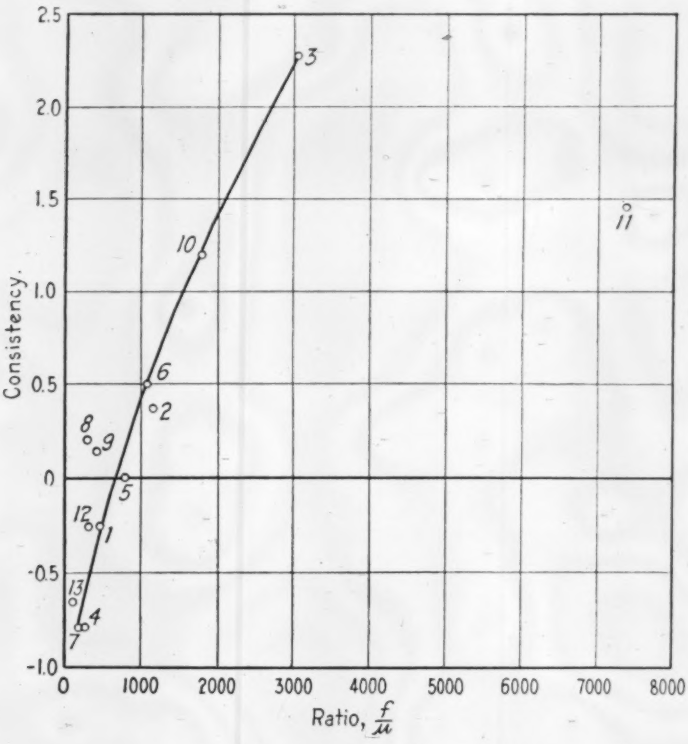

FIG. 6.—Relation between Consistency and the Ratio $\frac{f}{\mu}$.

11. In our investigation we have not concerned ourselves in regard to the point where, as the shearing stress is lowered, the values of the flow become too high to fall on the linear curve. The approximate values of these points are, however, given in Table XLI, since

the values here given show that the flow is normal when the shearing force is some 1300 dynes per cm^2 above the yield value. There is no evidence from these data that the point where the deviation begins varies with the size of the capillary.

The advantage that is gained by using a narrow capillary is discovered sooner or later by each investigator and the reason for it is now quite clear and cannot be over-estimated. Suppose, for example, that two different capillaries were used to measure the plasticity of the same paint, as illustrated diagrammatically in Fig. 7. The wide capillary gives the curve *ABO* and the narrow capillary the curve *DEO*. The linear portion of the curve *ABO* is too short to allow satisfactory extrapolation to the axis of abscissas, due to the limit placed on the rate of flow *FD* by the capacity of the plastometer. On the other hand, the linear part of the curve *DEO* is so long that the curved portion *EO* is of slight inconvenience and the necessary extrapolation is easy.

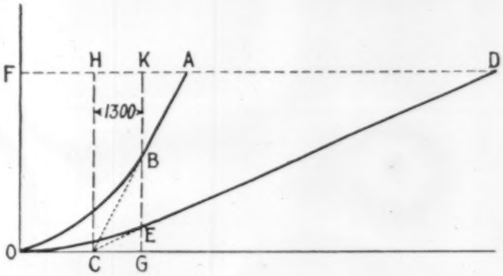

FIG. 7.

Dr. R. E. Wilson has reported that certain plastic solids with which he has worked, give no linear portion at any shearing stress employed. From our study it would appear that much finer capillaries should be employed using pressures as high as may be necessary. In the case of coarse materials the only recourse may be in using a much larger plastometer.

A consideration of other questions raised is being reserved for a later paper. We are greatly indebted to the E. I. du Pont de Nemours and Co. for materials and their generous support of this investigation. We are indebted to Dr. Edgar Buckingham for valuable criticisms.

DISCUSSION.

Mr. Green. MR. HENRY GREEN.—Mr. Bingham has given us a great deal to think about. We could talk for a long time on the various points presented, but I would like to mention only one, and that is the danger of trying to show plasticity as a comparable quantity. So far as I can see, it is a two-factor proposition—it is yield value and mobility—and we have always got to recognize it as such, I am afraid. I have often tried to put those two quantities together to get a unit which would define plasticity, but after working on it for several years my personal opinion is it will have to be given up.

Mr. P. H. Walker. MR. P. H. WALKER.—I can't exactly follow the argument for very great accuracy in the determinations of the mobility and the yield value. Now here we have in outside White No. 6 a yield value of from 60 to 520, and in the most of these paints we have something like that difference in yield value. Outside White A has a yield value of 120 to 370. Now, Mr. Bingham says that that proves that paints from the same grinding are not alike. It doesn't seem to me that his figures prove anything.

The Chairman. THE CHAIRMAN (MR. G. W. THOMPSON).—It seems to me that the indications are—I get this much—that there is a distinct yield point, as indicated by the prolongation of these straight lines, but where you have two different capillaries and you simply get a different angle between these two lines as obtained by the separate capillaries, the only thing which is common in those two observations is the yield point. Now, that being the case, in my poor ignorance, I wonder how you can get mobility.

Mr. Bingham. MR. E. C. BINGHAM.—Answering the Chairman, the yield value is obtained either by formula or graphically, as the intercept of the flow - shearing stress curve extrapolated. The mobility is calculated by Eq. 3 of our paper.

It is necessary to know the radius R of the capillary and its length l in order to calculate the shearing stress F from the pressure head P, thus

$$F = -\frac{RP}{2l}$$

as explained in our paper.

A point that needs emphasis is that the yield value, according to experimental results to date, is independent of the diameter of the capillary.

Mr. Bingham

Making use of our discovery that the shearing stress is the fundamental quantity to be considered rather than the pressure head, Mr. Buckingham has made a useful study to see whether the curvature at low shearing stresses can be explained on our present theory. Even though his efforts have not met unqualified success, this paper shows that at higher shearing stresses the flow-stress curves are linear, so the mobility is constant except at shearing stresses very near the yield value. If Mr. Buckingham's simple integration represented the facts exactly, the yield value as defined by him would be 0.75 of that used in this paper. But it is not certain that his integrations apply to particles whose radius is at all commensurate with the radius of the capillary. Moreover he has neglected seepage which is almost certainly a factor to be considered. So there is every reason for not being unduly disturbed over this curvature at very low rates of shear.

Answering Mr. Walker, the average deviation in our measurements is 0.69 per cent, there being no consistent variation when using a single paint with different capillaries. In the cases cited by Mr. Walker, paints taken from different cans, but supposed to be identical, gave a variation far greater than this in repeated measurements, so it seems fair to assume that some difference in treatment of the samples prior to their introduction into the plastometer may serve as explanation. These paints are quite complex and we have demonstrated that more than ordinary care will be necessary in the future to prevent undesired changes in plasticity.

Answering Mr. Green, I think that we must be very careful about specifying the ratio of yield value to mobility, because they are two independent variables.

The Chairman.

THE CHAIRMAN.—That paint which had the consistency of zero —can that be accepted as having the proper yield value and also the proper mobility?

Mr. Booge.

MR. J. E. BOOGE.—As I recall it, the paints close to zero did not always have the same yield values and mobilities. Higher yield values were compensated by higher mobilities and lower yield values by lower mobilities. There, it would seem that the ratio of the two is of value, a ratio of approximately 800 corresponding to satisfactory consistency.

The Chairman.

THE CHAIRMAN.—In other words, if I understand correctly, neither the yield value nor the mobility itself is a measure of the consistency of the paint.

Mr. Bingham.

MR. BINGHAM.—We have found a relation between the ratio (yield value to mobility) and the consistency, as measured by the committee. But perhaps we have not emphasized strongly enough that there was only one series of paints in which the yield value varied

Mr. Bingham. very much. Those that had an emulsifying agent present had a very high yield value but all of the others had yield values varying within very narrow limits. In other words, the paint-maker, when he doesn't put in an emulsifying agent, naturally prepares paints that have practically the same yield values.

Mr. Walker. MR. WALKER.—In reference to the ratio, mobility to yield value, as compared with the ratings of the committee, there is one of these paints, No. 5, rated by the committee as 0.0. No. 9 is the next nearest one to zero, which is 0.14. The ratio of the zero paint is 840 and of the 0.14 the ratio is 434. The next closest to zero is No. 8, rated by the committee at 0.20 with a ratio of 292. It seems to me that both the ratio and the yield value differ very widely among themselves.

Mr. Breyer. MR. F. G. BREYER.—There are a good many men here who should understand exactly what stage of development the plastometer is in at the present time. It is our opinion that this instrument is still a research aid and is not understood sufficiently to justify its use for routine testing. By that I mean that the difficulties that Mr. Bingham speaks of, the difficulties that have been brought out in the papers in the last two or three years, are not difficulties in the theory. They are difficulties in the actual carrying out of the mechanical process of obtaining the results. Now the first thing that the plastometer did was to demonstrate—and if it had done nothing else but to make that one demonstration the work on the plastometer as far as paints and varnishes are concerned would have been justified—that materials that have a structure within them, the pigment particles of which, or a single phase of which, is bunched, give yield values, and that paints in which the pigment particles or the disperse phase is deflocculated, that is, completely separated and wet by the liquid, give no yield value. That is a large accomplishment. Don't let us be confused by the fact that we are having a great deal of difficulty in getting these instruments to work clear out to both ends of a curve. We have a fairly good range to work with provided we don't derive too many conclusions. We have accomplished something by it already, and I think if we keep working somebody will come along and devise some simpler way of doing exactly the same thing, since this instrument has already analyzed the factors that determine plasticity. As I look at it to-day, if we couldn't get any further with the plastometer than we are there is a small chance of getting it adopted in the routine paint laboratory, but what I do think is that the plastometer is making an analysis of the consistency of paints possible, from which analysis someone is going to pick out a different method of arriving at that same result. That's the really hopeful thing in this work.

Mr. Herschel.

MR. W. H. HERSCHEL.—It is well for us to remember that there is a great deal more to be learned about the theory of plastic flow. I do not want to minimize the fact that Mr. Bingham's work has done a great deal to advance our knowledge of the consistency of plastic material. It is an immense step forward to realize definitely that you cannot express the properties of a plastic substance by a single numerical value. There are at least two elements and according to Mr. Buckingham in a paper presented last year[1] there are three.

Mr. Bingham.

MR. BINGHAM.—I agree with Mr. Herschel that the theory of plasticity as well as the practice has only been touched. We purposely kept away from the theory in this paper because this point has become somewhat controversial and we have too few facts upon which to reach a decision. When we extrapolate our curves to obtain a yield value, we are adhering closely to facts. We may find it desirable later to define the yield value differently but we are not likely to get a simpler definition.

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[1] E. Buckingham, "On Plastic Flow Through Capillary Tubes," *Proceedings*, Am. Soc. Test. Mats., Vol. 21, p. 1154 (1921).

SOME PHYSICAL PROPERTIES OF PAINTS.[1]

By P. H. Walker[2] and J. G. Thompson.[3]

Introduction.

The life of any paint may be divided into three stages or periods: (1) the period of storage intermediate between manufacture and application, (2) the period of application when the paint is spread out in a thin, wet film, and (3) the period of exposure covering the life of the dry paint film. Each period is characterized by certain physical properties which indicate the value of the paint. During the first period little information of value is obtainable, but even here certain defects in manufacture or material may be indicated by such phenomena as flocculation, caking, or excessive settling. It is during the second period that the really valuable physical properties, such as the wetting power or adherence to the surface, ease of application, hiding power, color, uniformity, gloss, spreading rate, and rate of drying first appear. In the final stage of the life of the paint the only factors with which we are concerned are those which affect the permanence or stability of the film established as a result of the properties which appear and function during the second period. We know that all of these properties are important, but few if any can be measured with any degree of accuracy, and most of the properties are tested by methods in which the personal equation is so large that reproducible results can not be obtained. Any study of the physical properties of paints necessarily must begin with a standardization of tests and consequently our attention at present will be confined to a very few of the properties mentioned above.

Plastometer Measurements.

The first attempt to investigate these physical properties consisted of a study of the possibilities of the plastometer, as described by Bingham and Green[4] and by Green.[5] The yield values and mobilities for a considerable number of paints were determined by means of the plastometer but the interpretation of these results in connection with the life and value of the paint film was not successful. It is obvious that rapid changes in the composition and properties of a paint begin to occur as soon as the process of application begins and continue until the volatile matter has disappeared, the chemical changes have been completed, and the film has reached its final permanent condition. On the other hand, a sample of paint in the plastometer is held in a closed system which prevents the occurrence of these changes. Consequently it is difficult to establish any connection between the properties or behavior of the wet paint in the plastometer and the properties or behavior of the same paint under the conditions of actual application. The plastometer undoubtedly will furnish valuable assistance and information to a manufacturer in the study of a paint during the first stage in its life, or in the reproduction from similar constituents of a paint previously prepared. No connection is apparent, however, between the yield and mobility values as determined by the plastometer and the actual service value of the paint. Consequently it seemed advisable to turn our attention to a direct study of paint films.

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[1] Published by permission of the Director, U. S. Bureau of Standards.

[2] Chemist, U. S. Bureau of Standards, Washington, D. C.

[3] Associate Chemist, U. S. Bureau of Standards, Washington, D. C.

[4] E. C. Bingham and Henry Green, "Paint, A Plastic Material and not a Viscous Liquid; the Measurement of Its Mobility and Yield Value," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II, p. 640 (1919).

[5] Henry Green, "Further Development of the Plastometer and Its Practical Application to Research and Routine Problems," *Proceedings*, Am. Soc. Test. Mats., Vol. XX, Part II, p. 451 (1920).

THE PREPARATION OF PAINT FILMS.

In view of the number and importance of the properties which first become evident at the time of application, it is obvious that this second stage in the life of a paint forms the logical starting point for any investigation. The physical properties which combine to determine the consistency or behavior of a paint at the time of application are of fundamental importance, but before any comparative study of a number of paints could be undertaken it was necessary to devise some reproducible method of preparing paint films. Flowing produces satisfactory results but unfortunately is limited to a very few of the thinnest paints. The ordinary methods of brushing and spraying are unsatisfactory since the resulting films are never uniform and can be duplicated only by accident. Some mechanical means therefore must be employed and as a result of some promising preliminary experiments the idea of using centrifugal force was adopted.

A number of circular glass plates furnished the standard surfaces to be covered with paint. These plates were each 25 cm. in diameter and approximately 1 cm. thick. The surfaces were ground flat and finished by fine grinding but were left unpolished, to furnish a surface to which the paints would adhere readily. In the earlier work steel plates were used interchangeably with the glass plates but were later discarded, as the glass proved to be much easier to handle and to keep clean.

The apparatus employed consists of a vertical spindle rotated by a belt connected with a variable speed motor. To the upper end of the spindle is fastened a circular wooden block to support the glass plate which is held in position by several small screw hooks at the circumference of the wooden block. The plate is brought up to constant speed and an excess of paint, previously screened through a 200-mesh sieve to insure uniformity and freedom from skins, is poured on at the center of the plate. The paint flows out, covers the surface, and the excess is thrown off. The motor is then stopped and the plate removed and allowed to dry. After the paint is dry the film thickness[1] is determined by means of an Ames dial gage, reading direct to 0.01 mm. and estimating to 0.001 mm.

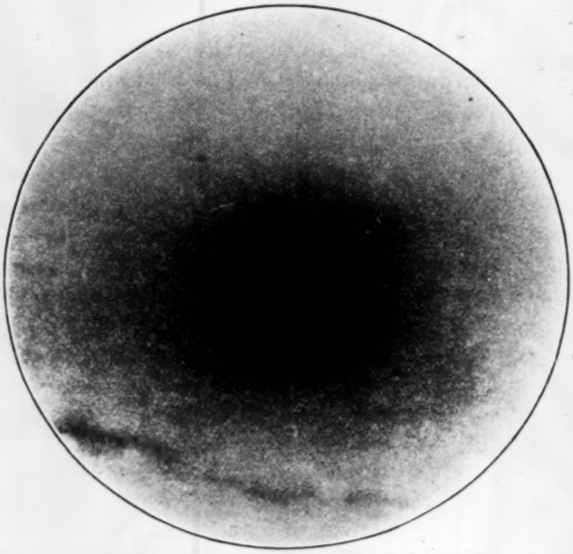

FIG. 1.—Typical Oil Paint Film. Paint No. 74088 (Table I). 200 r.p.m.

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[1] In any comparison of paints it must be borne in mind that the wet and dry films of any one paint will differ in thickness, depending upon the amount of volatile matter in the vehicle. The thickness of the dry film is a measure of the consistency of the wet paint only when the vehicle contains no volatile thinners. Since volatile thinners almost invariably are present, the observed thickness of the dry film must be increased in proportion to the amount of volatile matter in order to obtain results upon which comparisons of the wet paints may be based.

At any given speed, the centrifugal force increases directly with the distance from the center of rotation. One would expect, therefore, that the resulting film would be thinnest at the circumference of the plate and would reach a maximum at the center. This is what usually occurs and the resulting film is generally pyramidal, although the pyramid does not extend uniformly over the entire surface. The film usually presents the appearance of a large, flat plane with a small, sharply defined pyramid at the center. In other words, starting at the circumference the film increases very gradually in thickness until a point near the center is reached. Beyond this point the film increases suddenly and markedly to a maximum value for that particular paint and speed. The pyramidal film which is characteristic of most paints, illustrated in Fig. 1, is not produced by varnishes nor by liquids such as linseed oil. These give flat films of uniform thickness across the entire surface, in spite of the fact that the centrifugal force varies widely at different points on the plate. Fig. 2 shows a photograph of the flat, uniform film produced by an enamel. Table I indicates numerically the various types of films produced by different materials.

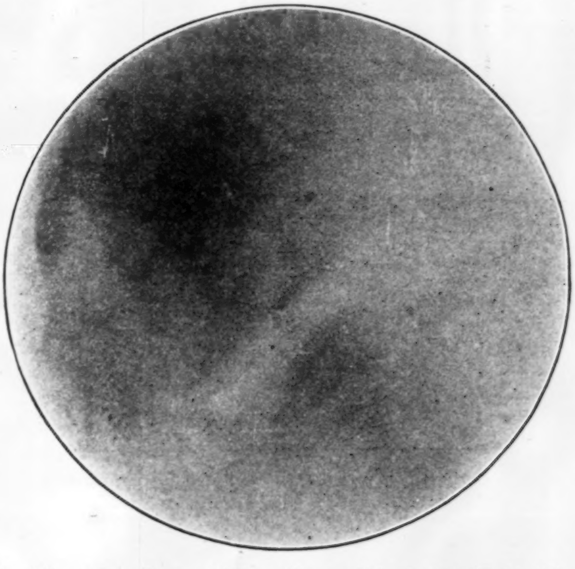

FIG. 2.—Typical Varnish or Enamel Film. Enamel No. 74082 (Table II). 400 r.p.m.

The flat films characteristic of the oils and varnishes form while the plate is in motion and are not due to the action of surface tension or any other force after the plate has come to rest. This was shown by continuous whirling of a quick-drying varnish (No. 73521 in Table I) until the film was hard and dry. This dry film was perfectly flat and showed no indication of any pyramid at the center. The enamels appear to occupy an intermediate position between the flat varnish or oil films and the pyramidal paint films, some of the enamels being perfectly flat, others distinctly pyramidal.

Effect of Amount of Paint Used.—Numerous experiments performed with varying amounts of paint led to the conclusion that the film thickness is independent of the amount of paint applied. An insufficient amount of paint will cover only a portion of the surface while an excess of paint will cover the entire surface and the excess be thrown off. The resulting films in both cases are of equal thickness at corresponding points, but for the sake of convenience it is advisable always to use a slight excess of paint to insure covering of the entire surface.

TABLE I.—TYPICAL FILMS OF DIFFERENT MATERIALS.

Materials.	Film Thickness, mm., at Distance from Center of Plate Indicated.			
	10 cm.	7.5 cm.	5 cm.	2.5 cm.
Raw Linseed Oil	0.016	0.017	0.017	0.015
Varnishes:				
No. 73521	0.023	0.024	0.025	0.024
No. 72754	0.029	0.029	0.030	0.029
No. 72759	0.040	0.041	0.040	0.040
Enamels:				
No. 74094	0.029	0.029	0.029	0.029
No. 74082	0.080	0.083	0.087	0.090
Oil Paints:				
No. 74090	0.028	0.030	0.032	(Too thick to dry properly.)
No. 74089	0.046	0.055	0.070	
No. 74088	0.067	0.079	0.104	

Effect of Speed of Rotation.—The centrifugal force increases as the square of the angular velocity so that one would expect the film thickness to decrease as the speed increases. The data in Table II illustrate the variations actually encountered when the speed is varied. At speeds of 200 r.p.m. or less many paints produce films too thick to dry properly. Too high speeds cause segregation of the pigment particles and in some extreme cases a tendency to disrupt the film has appeared. A speed of 300 r.p.m. seems to be the most generally satisfactory, producing a minimum number of sandy, segregated films and a negligible number of thick wrinkled films.

Effect of Time of Rotation.—The film thickness is practically independent of the time of whirling after the first short interval of time has elapsed. Under normal conditions practically all of the excess paint will be thrown off during the first half minute of whirling, after which only an occasional drop is thrown off. The time necessary to reach equilibrium, of course, varies with the speed and with the mobility of the paint; the lower the speed and the lower the mobility the greater will be the time required. Working with ordinary paints at a speed of 300 r.p.m., it was found that three minutes' whirling invariably provided a comfortable margin of safety beyond the time necessary to reach equilibrium. Table III presents data illustrating the change in film thickness with time of whirling. This paint was considerably thicker and less mobile than the ordinary paints, but even in this case it is evident that the changes occurring after three minutes are negligible as compared with those occurring during that time.

Uniformity and Reproducibility of Films.—The most satisfactory feature of the results obtained is the uniformity of film thickness produced at points subjected to the same forces and the agreement obtained in duplicate experiments. In Table IV each vertical column shows the range of variation for points subjected to the same spreading forces while a comparison of the two sets of average values shows the extent to which the results can be reproduced.

TABLE II.—VARIATION OF FILM THICKNESS WITH SPEED OF ROTATION.
Paint No 74082.

Speed, r.p.m.	Film Thickness, mm., at Distance from Center of Plate Indicated.			
	10 cm.	7.5 cm.	5 cm.	2.5 cm.
400	0.049	0.051	0.054	0.055
300	0.061	0.063	0.064	0.067
200	0.080	0.083	0.087	0.090

The use of centrifugal force as a means of preparing reproducible paint films has been highly satisfactory. The resulting films furnish a basis for comparison of the consistency or resistance to spreading of the paint. The pyramidal films should be suitable for a study of other properties such as opacity, color, and time of drying, and it is hoped that in the future this investigation may be extended to include these various properties. The most satisfactory features of this method are the uniformity of the films produced and the ease and certainty with which they can be duplicated.

A satisfactory explanation for the different types of films has not been obtained. It is practically impossible to determine the forces acting at any particular point, owing to lack of information as to the size and range of effectiveness of the forces of adhesion and cohesion. It would seem that the thickness of the film as a whole must be connected with the wetting power and mobility of the paint while the height of the central pyramid may be an indication of the yield value. More data are needed before final conclusions can be drawn.

THE EFFECT OF VARYING COMPOSITION ON PAINT FILMS.

Our next investigation was a study of the effect produced upon the life and behavior of a paint film by varying the proportions of pigment and oil in the film. For comparative purposes the films should be of equal thickness and the use of centrifugal force as previously described furnishes a convenient means for determining the film thickness which will result when any paint is spread under certain selected conditions. If several paints produce films of equal thickness when whirled at the same speed it may be assumed that those paints will produce comparable films when brushed out on test panels. The object sought was to produce a series of paints of varying oil-pigment ratios thinned with turpentine until they would spread or brush out to produce dry films of equal thickness.

TABLE III.—VARIATION OF FILM THICKNESS WITH TIME OF ROTATION.

Paint No. 72204. Speed, 420–440 r.p.m.

Time, minutes.	Film Thickness, mm., at Distance from Center of Plate Indicated.			
	10 cm.	7.5 cm.	5 cm.	2.5 cm.
½	0.054	0.058	0.063	0.076
1	0.047	0.049	0.055	0.067
2	0.041	0.043	0.047	0.059
3	0.039	0.042	0.047	0.057
4	0.037	0.041	0.044	0.055
5	0.037	0.039	0.043	0.054
60	0.036	0.039	0.046	0.056

Four pigments were selected for study:

(*a*) Basic carbonate white lead, B. S. Lab. No. 45724;
(*b*) Zinc oxide, B. S. Lab. No. 45714;
(*c*) 60 per cent basic carbonate white lead, 40 per cent zinc oxide;
(*d*) 60 per cent basic carbonate white lead, 30 per cent zinc oxide, 10 per cent asbestine.

Each pigment was ground to a paste with a normal amount of raw linseed oil. Each paste was divided into several weighed portions and varying amounts of oil were added to the different portions until the resulting series of semi-pastes or semi-paints represented a range of pigment content varying from 15 to 50 per cent by volume,[1] the corresponding limits for the oil being 85 and 50 per cent by volume. Liquid drier was added to each semi-paint in the proportion of 5 cc. of drier to 95 cc. of oil. The various semi-paints were listed and assigned serial numbers as shown in Table V.

These semi-paints varied in consistency from pastes such as Nos. 8, 16, 24, and 32 to extremely thin paints such as Nos. 1 and 2. Some one mixture had to be chosen as an arbitrary standard and No. 3 was adopted, since this mixture behaved well under the brush and produced a film of satisfactory appearance and properties. The other mixtures were thinned with turpentine until they produced the same film thickness as No. 3 when whirled at the same speed. The turpentine being volatile serves merely to increase temporarily the mobility of the paints and later evaporates, leaving films of the composition shown in Table V.

TABLE IV.—REPRODUCIBILITY OF RESULTS.

Paint No. 9-B. Speed, 300 r.p.m.

	Plate No. 6.				Plate No. 1.			
	Film Thickness, mm., at Distance from Center of Plate Indicated.				Film Thickness, mm., at Distance from Center of Plate Indicated.			
	10 cm.	7.5 cm.	5 cm.	2.5 cm.	10 cm.	7.5 cm.	5 cm.	2.5 cm.
	0.026	0.030	0.038	0.053	0.025	0.030	0.033	0.054
	0.027	0.026	0.035	0.055	0.028	0.032	0.030	0.057
	0.026	0.031	0.030	0.059	0.029	0.029	0.030	0.059
	0.026	0.029	0.031	0.065	0.029	0.027	0.031	0.059
	0.027	0.025	0.032	0.061	0.026	0.025	0.031	0.056
	0.024	0.026	0.031	0.059	0.029	0.030	0.033	0.052
	0.025	0.029	0.034	0.051	0.027	0.030	0.034	0.050
	0.027	0.026	0.034	0.051	0.026	0.029	0.033	0.057
Average	0.026	0.028	0.033	0.057	0.027	0.029	0.032	0.055

The adjustment of the basic carbonate white lead series by the addition of turpentine was first attempted. It was found that No. 8, containing the most pigment and the least oil, required the addition of 40 cc. of turpentine to 100 cc. of oil-pigment mixture to produce a dry film of the same thickness as No. 3, the standard. The mixtures intermediate between Nos. 3 and 8 increase successively in ratio of pigment to oil so that it was natural to assume that the turpentine requirements would increase successively from zero for No. 3 to the 40 cc. required by No. 8. This proved to be a fact. Similar reasoning did not hold in the cases of the zinc oxide and mixed pigments and we were forced to adopt an empirical method, adding the turpentine in

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[1] Computations were based on the data given by Gardner and Parks, *Circular No. 104*, Paint Mfrs. Assoc. of the U. S., September, 1920.

5-cc. portions until the desired film thickness was obtained. The composition of the final paints obtained by this method is also shown in Table V.

This series of paints was made up, brushed out on a series of panels and the panels exposed to the weather on January 14, 1922. In the six weeks which have elapsed since that date, no defects have appeared aside from the tendency to collect dirt exhibited by all of the white lead paints and especially by those which contain greater proportions of oil.

TABLE V.—COMPOSITION OF SEMI-PAINTS AND PAINTS.

Pigment.	Semi-Paint No	Percentage by Volume.		Volume of Turpentine Added to 100 cc. of Semi-Paint, cc.	Paint No.
		Pigment.	Oil.		
Basic Carbonate White Lead	1	15	85	(Discarded. Too thin)	
	2	20	80	(Discarded. Too thin)	
	3	25	75	0 (Standard)	3 *a*
	4	30	70	8	4 *a*
	5	35	65	16	5 *a*
	6	40	60	24	6 *a*
	7	45	55	32	7 *a*
	8	50	50	40	8 *a*
Zinc Oxide	8 *x*	12.5	87.5	0 (O. K.)	8 *x a*
	9	15	85	10	9 *a*
	10	20	80	30	10 *a*
	11	25	75	55	11 *a*
	12	30	70	70	12 *a*
	13	35	65	80	13 *a*
	14	40	60	92.5	14 *a*
	15	45	55	95	15 *a*
	16	48.2	51.8	97.5	16 *a*
60 per cent Basic Carbonate White Lead; 40 per cent Zinc Oxide	17	15	85	(Discarded. Too thin)	
	18	20	80	0 (O. K.)	18 *a*
	19	25	75	20	19 *a*
	20	30	70	35	20 *a*
	21	35	65	50	21 *a*
	22	40	60	57.5	22 *a*
	23	45	55	65	23 *a*
	24	50	50	75	24 *a*
60 per cent Basic Carbonate White Lead; 30 per cent Zinc Oxide; 10 per cent Asbestine.	25	15	85	(Discarded. Too thin)	
	26	20	80	0 (O. K.)	26 *a*
	27	25	75	20	27 *a*
	28	30	70	35	28 *a*
	29	35	65	47.5	29 *a*
	30	40	60	57.5	30 *a*
	31	45	55	65	31 *a*
	32	50	50	75	32 *a*

THE THINNING POWER OF TURPENTINE.

The preparation of the paints described in the preceding section resulted in some interesting observations. As expected, it was found that the thinning power of turpentine varies with the different pigments, but it was rather surprising to find a variable thinning power for any one pigment depending upon the composition of the vehicle already present, as appeared in the cases of the zinc oxide and mixed pigments. It is difficult to draw conclusions regarding the consistency of the paints from the data in Table V, since the thickness of the wet films will vary widely although the dry films are all of equal thickness. For instance in the case of paints Nos. 3*a*, 8*x a*, 18*a* and 26*a*, the wet and dry films may be assumed to be of equal thickness, since no volatile matter is present, while the wet film produced by No. 16*a* would be approximately twice as thick as the dry film left after the evaporation of the turpentine. Nevertheless there is unmistakable evidence that the thinning power of turpentine not only varies with different pigments but also varies for any one pigment with the composition of the mixture being thinned. Assuming that the mobility of a paint is proportional to the viscosity of the vehicle, this would indicate that the viscosity of turpentine-raw linseed oil mixtures is not a linear function of the composition. Accordingly the viscosity-composition curve for oil-turpentine mixtures was determined by means of a Saybolt viscosimeter. The resulting curve (Fig. 3) shows that the first portion of turpentine added to an oil-pigment mixture has a much greater thinning action than any subse-

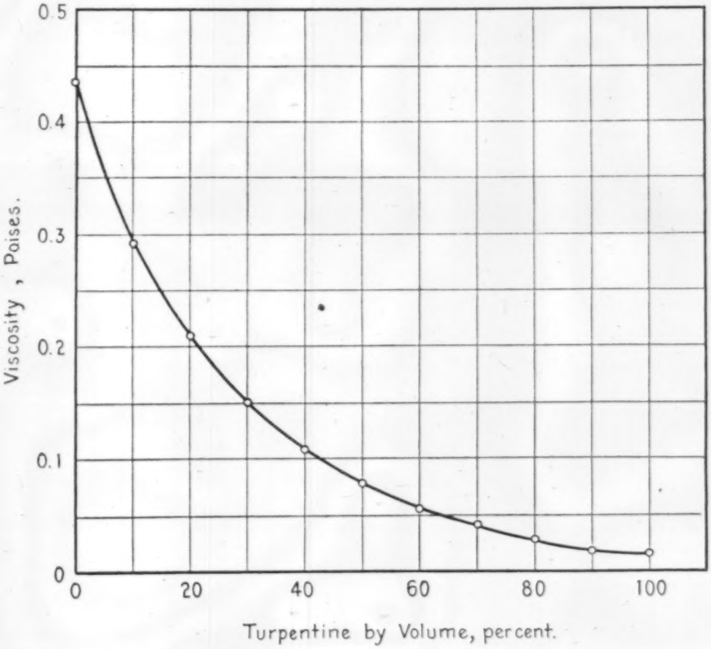

FIG. 3.—Viscosity-Composition Curve for Mixtures of Turpentine and Raw Linseed Oil at 25° C.

quent portion and that after the turpentine content of the vehicle reaches 50 or 60 per cent, further additions of turpentine have little or no effect on the consistency of the paint. The apparent constant thinning power of the turpentine in the case of the white lead paint represents experimental error due to lack of sensibility in the method of determination. The largest amount of turpentine employed in preparing the white lead paints is just approaching the sharp bend in the curve where the variable effect first becomes easily recognizable. In the cases of the other pigments the composition of the vehicle corresponds to points further along on the flat portion of the curve and consequently the variable thinning power of turpentine is more readily apparent.

THE AGING OF BASIC CARBONATE WHITE LEAD PAINTS BEFORE APPLICATION.

It is generally believed that a paint resulting from the thinning or breaking up of a basic carbonate white lead paste should be allowed to stand for a day or two before being used. The probable reason for the origin of this belief was found when a white lead-oil-turpentine paint was used immediately after mixing, flowing the paint on a clean glass plate to form a smooth wet film. In the course of a few minutes small pits appeared on the surface of the film and gradually increased in depth and diameter until the film assumed the appearance shown in Fig. 4 (*a*). The original surface was never bared, being covered with a thin, transparent film of oil at the bottom of the pits, but the paint film was worthless either for protection or decoration. The phenomenon appeared over and over and could not be ascribed to any fault in the preparation of the surfaces painted. The same result was obtained no matter whether the paint was applied to glass, steel, or to a previously dried coat of paint.

The trouble is not connected with the rate or amount of mixing. Several paints of the same composition were stirred for variable periods, from the minimum stirring by hand necessary to insure a uniform mixture to a maximum of 70 minutes violent mechanical stirring. No appreciable difference was apparent as a result of the variable amounts of stirring, indicating that the trouble is not caused by lack of stirring. Vigorous stirring of a paint which had ceased to spot did not bring back the spotting tendency, showing that the trouble is not caused by too much stirring.

This effect evidently is produced within the paint, and a number of experiments were carried out in an attempt to locate the constituent or constituents causing the trouble. The tendency to pit appears to result whenever basic carbonate white lead and raw linseed oil are brought together. It may be modified to some extent by the composition of the vehicle but is always present. Fig. 5 (*a*) shows a slightly different manifestation of the same tendency in the case of a thicker paint applied with a brush.

Different samples of white lead paste of varying age and varying oil content all behaved approximately alike. The presence of liquid driers sometimes reduces the tendency but never eliminates it. The presence or absence of turpentine in the vehicle usually has no effect. The trouble does not appear when boiled linseed oil is substituted for the raw oil. Basic carbonate white lead is the only pigment which has shown this tendency; various samples of ochers, siennas, blacks, and white pigments other than basic carbonate white lead all could be used immediately after mixing. Mixtures of basic carbonate white lead with other white pigments usually gave trouble when the white lead content was high but did not invariably do so.

The following experiments indicate that the source of the trouble is located in the oil rather than in the pigment. An oil-pigment mixture was made up and allowed to stand several days until the pigment settled, leaving a layer of clear oil on top. This oil was separated from the pigment, paints were made up and examined for spotting, as follows:

(*a*) Treated oil and treated pigment;
(*b*) Treated oil and fresh pigment;
(*c*) Fresh oil and treated pigment;
(*d*) Fresh oil and fresh pigment.

Both paints made with fresh oil spotted readily; neither paint made with the treated oil spotted at all, showing that the troublesome constituent is located in the oil and indicating the possibility of curing the oil by agitating with basic carbonate white lead during storage prior to use.

Different samples of raw linseed oil all showed the same tendency although it was more marked in some cases than in others. The ordinary analytical determinations furnish no explanation of the different behavior of the oils. It was thought that the acid number of the oil might have some influence on this spotting tendency, so a series of oils having acid numbers of 3, 6, 12, and 24 was made up by adding to the raw oil calculated amounts of free fatty acids prepared from linseed oil according to the method of Steele and Washburn.[1] Each of these oils was used to thin a white lead paste to painting con-

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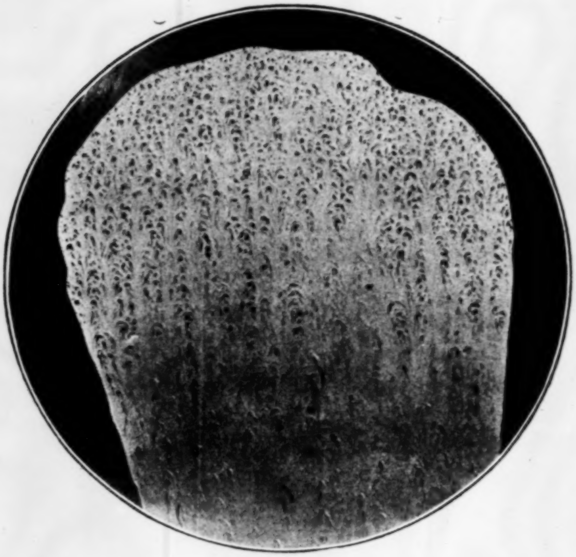
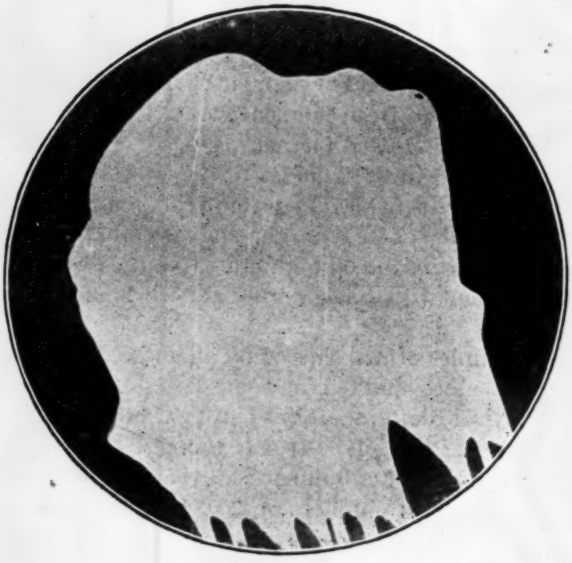
[1] Steele and Washburn, *Journal Industrial and Engineering Chemistry*, Vol. 12, p. 52 (1920).

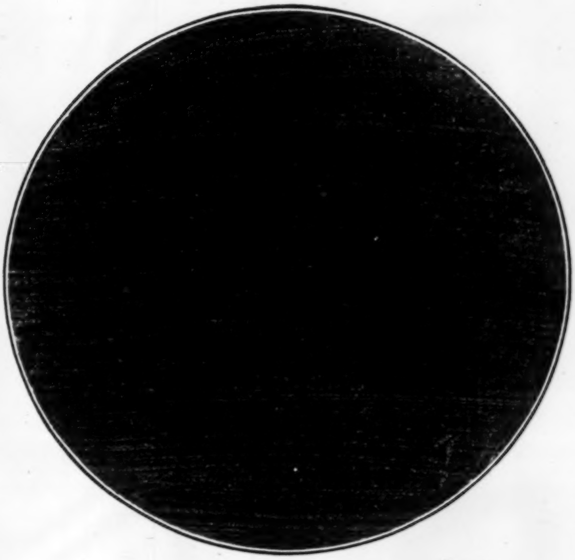


(*a*) Freshly Mixed.

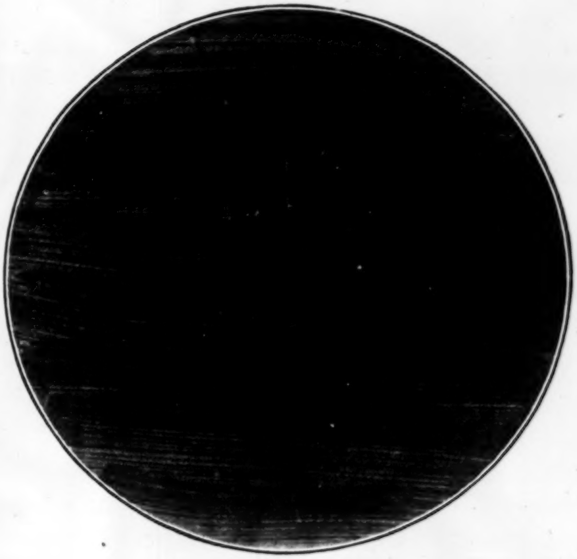


(*b*) Aged.

FIG. 4.—Basic Carbonate White Lead Paint with Raw Linseed Oil, Flowed.



(*a*) Freshly Mixed.



(*b*) Aged.

FIG. 5.—Basic Carbonate White Lead Paint with Raw Linseed Oil, Brushed.

sistency and in one case the free fatty acids (acid No.[1], 199) were used instead of oil to thin the paste. All of the resulting paints "spotted." The paint resulting from the complete substitution of fatty acids for linseed oil spotted the least, the others all spotted to about the same extent, showing that the spotting tendency is not proportional to the acid number of the oil.

The presence of traces of water in the oil was considered as a possible source of the trouble. A sample of raw oil was freed from water by heating for three hours at a temperature of 105 to 110° C., an atmosphere of CO_2 being maintained to prevent oxidation of the oil. Another sample of the same oil was saturated with water by adding an excess of distilled water and shaking for about 30 minutes. Some hydrolysis of the oil occurred which produced a stable, cloudy emulsion of oil and water floating on the excess of water. Portions of the water-free, water-saturated, and untreated raw oil were made into paints and the films compared. The water-free and untreated oils both spotted readily while the water-oil emulsion showed only faint traces of surface pits. A portion of the water-oil emulsion was filtered through paper, breaking up the emulsion and producing a clear oil, the water apparently being retained by the filter paper. This filtered oil produced a spotted film similar to the water-free and untreated oils and much inferior to the film produced by the oil saturated with water. It appears therefore that the absence of water does not remedy the tendency to spot; in fact the presence of water may be desirable as far as the spotting tendency is concerned.

Small amounts of free mineral acids were added to portions of the raw oil and the resulting oils were made into paints. The results were indeterminate, owing to the liberation of carbon dioxide and the change in the nature of the pigment resulting from the action of the acids on the basic carbonate white lead. It is difficult to believe that this spotting tendency is due to gas bubbles, which would be the obvious result of the presence of free mineral acids. Gas bubbles would form in the body of the film and would be visible below the surface. When the gas pressure finally became great enough to disrupt the surface film the gas would escape and the paint would flow together again. What actually happens is that small pits appear first in the surface film, gradually and continually increasing in depth and diameter, which is just the reverse procedure from that shown during the formation of bubbles. No bubbles have been observed when the films spotted.

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[1] Acid number means the milligrams of KOH required to neutralize 1 g. of material.

The only available samples of commercial boiled linseed oil produced good paint films, none of which showed any tendency to spot. The difference between raw and boiled oils may be due to the presence of driers in the boiled oil or to whatever changes are produced by the heat alone. Accordingly, samples of raw oil were boiled both with and without driers at 110° C. and at 260° C. The samples boiled at 110° C. with and without driers spotted readily, and the sample boiled at 260° C. without drier spotted somewhat worse than the other two, while the oil boiled at 260° C. in the presence of driers did not spot.

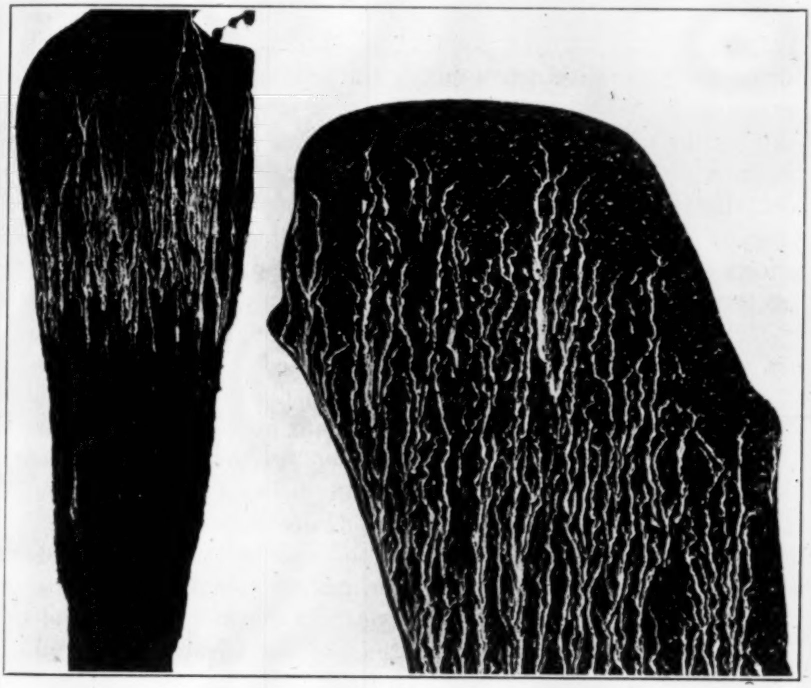

FIG. 6.—Unsatisfactory Paints.

Apparently the combined action of heat and driers will cure the spotting tendency but neither one alone can accomplish the desired result.

When raw oil is used, the only remedy appears to be aging. Every paint which gave a spotted film when freshly mixed gave a perfect film after standing for a while. Figs. 4(*b*) and 5(*b*) show the paints illustrated in Figs. 4(*a*) and 5(*a*) after aging. Twenty-four hours' aging before application prevented spotting of the great majority of the paints examined and the few which still spotted slightly at the end of 24 hours produced good films at the end of an additional

24 hours. No paint has been found which exhibited this tendency 48 hours or more after mixing.

There appears to be some portion or constituent of the oil, as yet unidentified, which combines or reacts in some way with the white lead, creating forces which cause partial disruption of the film and segregation of the pigment away from the affected areas. This reaction proceeds slowly and requires a certain length of time to reach completion. The conclusion has been reached that the trouble is probably caused by the reaction with the basic carbonate white lead of some of the unsaturated bodies present in the oil. The trouble is eliminated when the compounds are saturated with the pigment during aging, or with driers during the boiling process at high temperatures. The improvement in the case of the oil-water emulsion may be due to the concentration of the troublesome constituents in the interphase of the emulsion, to some extent preventing contact with the pigment. It would be interesting to follow the effect of different methods of blowing and boiling samples of the same oil, but unfortunately equipment for these experiments is not available in this laboratory.

This phenomenon should not be confused with the defects exhibited by the type of poor paint usually classed as "runny," nor with the somewhat similar appearance occasionally encountered in commercial paints as shown in Fig. 6. These paints had been thoroughly aged and were of satisfactory composition as shown by the ordinary analytical determinations. It is generally believed that such unsatisfactory paints are due to improper preliminary treatment of the oils or to inadequate or improper incorporation of the constituents to form the finished paint. When the materials or treatment are at fault the resulting conditions are permanent and the properties of the paint never improve. In the case of the white lead and linseed oil the trouble is wholly temporary and will remedy itself if given time enough.

Summarizing these observations it appears that the spotting tendency:

(*a*) Is common to all mixtures of basic carbonate white lead and raw linseed oil;

(*b*) Does not appear when other pigments are substituted for the basic carbonate white lead;

(*c*) Does not appear when other oils are substituted for raw linseed oil;

(*d*) Is not due to too much stirring or to lack of stirring; presence or absence of liquid driers and volatile thinners; order of mixing;

presence of free fatty acids, mineral acids, or water, although any or all of the foregoing factors may at times exert a modifying influence;

(*e*) May be explained upon the assumption of a reaction between the basic carbonate white lead and some unidentified portion of the oil;

(*f*) May be eliminated by boiling the oil in the presence of driers which may convert the troublesome component to an inactive form; by treating the raw oil with basic carbonate white lead during storage prior to its use; or by aging the paint to allow the reaction to reach completion before the paint is applied.

CONCLUSION.

The preceding observations are offered as the first results of investigations, dealing with the physical properties of paints. They are presented with the hope of promoting discussion and the exchange of ideas with other investigators.

DISCUSSION.

Mr. Croll. MR. P. R. CROLL.—It wasn't very clear to me in just what manner the authors expected to use the results of the plastometer. I believe I understood Mr. Thompson to say that a prediction of the life value of paint films was to be obtained, or to be hoped for, from plastometer measurements. I fail to understand how that could possibly be ever hoped for.

Regarding the very interesting pitting of white lead, I was surprised to note the depth and degree of this pitting as evidenced by the photographs. I had forgotten until then the experience of our laboratory using the old spot test method for determining "body." Eight or ten years ago all pigments including zinc and lithopone were mixed with a standard proportion of white lead before the old running test was applied. Often, especially when dry white lead had been used, a pitting of the paint was observed, but, whenever these freshly prepared pastes had been allowed to age, the pitting was no longer noticed. Again, when paste lead instead of dry lead had been used, no pitting took place. To those who have seen the results of flocculation, both on films and in the paint can, the photographs are extremely characteristic. The cause of pitting is most certainly due to a flocculation of the pigment.

In order to answer the question why dry white lead freshly ground in raw linseed oil should be strongly flocculated and later become dispersed, we reviewed our work on the effect of zinc and lead soaps and find a rather easy explanation. It was found that both lead and zinc soaps dissolved or suspended in linseed oil accordingly increased the dispersing action of the oil itself, not only to white lead but to all other pigments. In the case of very fine pigments, such as zinc oxide, this dispersion was found so nearly complete as to seriously interfere with the separation of pigment and vehicle during the analysis.

The Chairman. THE CHAIRMAN (Mr. G. W. Thompson).—I would like to say that the phenomenon described about white lead was observed by me a great many years ago, and I got the impression that it was in the nature of crawling. If you take one of these spots and magnify it, it looks very much like what you get in varnish crawling. Perhaps those who are experienced with varnish can tell us more about the crawling

The Chairman. of varnish, but the general opinion is that fresh varnish is more apt to crawl than aged varnish, and it is just a question as to whether if you take two different varnishes and mix them, you would not get crawling. In other words, we think of liquids as easily mixable. On the other hand, we have been told that there are such things as liquid crystals. In other words, parts, molecules or groups of molecules in liquids may tend to arrange themselves or orient themselves in some way which will show certain optical results. In this particular case, apparently, the time element is necessary to bring about a proper dispersion of the oil which was in the white lead originally, with the oil which was added. Now you would think you could accomplish all that by simple mixing. Apparently you can't do it with varnishes, and you can't expect to do it with white lead.

Mr. Bingham. MR. E. C. BINGHAM.—I do not think that we can longer hold that the viscosity of a mixture of two substances is normally a linear function of the concentration, but a variety of causes may prevent even that from being the case.

I should like to propose as an alternate explanation for the phenomenon which was found the difference in wetting power, that is, in specific adhesion of turpentine and the vehicle that was present with those pigments. The character of the paint is entirely altered when turpentine is added, provided that the vehicle was a pure linseed oil.

I should like to ask the author if he tried any paints which had present an emulsifying agent. Since such paints have a higher yield value we might expect those particular paints to give a greater thickness of film than the others.

Mr. Chapman. MR. CLOYD M. CHAPMAN.—May I call attention to one matter in connection with this subject of viscosity? The paper states, "The resulting curve [referring to the viscosity curve, Fig. 3] shows that the first portion of turpentine added to an oil pigment mixture has a much greater thinning action than any subsequent portion and that after the turpentine content of the vehicle reaches 50 or 60 per cent, further additions of turpentine have little or no effect on the consistency of the paint." If we examine this curve, it will be noted that the first addition of twenty per cent reduced the viscosity from 4 down to 2—cut it in half. The next addition of twenty per cent again cuts the viscosity in half or down to 1. Another twenty per cent addition cuts that in half, down to one-half. Another twenty per cent brings the viscosity down to a quarter. Each addition of twenty per cent virtually cuts the viscosity in half, showing that the equal added increments of turpentine have an equal effect on the viscosity.

Mr. Nelson.

MR. H. A. NELSON.—In our laboratories we have been, for some time, working on the preparation of uniform paint films by flowing, brushing or spraying. This has finally resolved itself into a cut-and-try method demanding an operator so trained that he can turn out fairly uniform films after a few trials. What I would like to suggest is that it might be possible to take measurements of the yield value and mobility of a paint and from these, by previous calibration, determine how fast and how long a disk must be whirled in order to obtain a film of definite thickness. If this has not been tried, I think it of sufficient interest to be given some attention.

Mr. J. G. Thompson.

MR. J. G. THOMPSON.—Our laboratory is interested primarily in the testing of paints, and consequently, in their behavior during application. Our point of view was that the plastometer determinations, as made in the closed system corresponding to the paint in the can, do not have any apparent relation to the behavior of the paint during application. Consequently we thought we could get better results by turning our attention to something which would have a more obvious relation to the actual performance of the paint, and that was our reason for abandoning the plastometer.

In answer to Mr. Nelson, we have attempted to correlate the yield and mobility values with the nature of the film produced by the use of centrifugal force, but have not been successful in these attempts as yet. It would seem that some relation between these properties must exist, but the relation is not obvious from our data.

Regarding the viscosity-composition curve for turpentine and linseed oil, we did not mean to infer that we expected to find a straight line relationship. We found experimentally that equal successive additions of turpentine did not produce equal thinning effects in certain of our paints and the viscosity-composition curve, determined subsequently, shows graphically why this condition exists. We thought it worth while to include this curve in the present paper as we are not aware of any previous attempts to call attention to this particular point.

I do not know that we have tried any paints containing emulsifying agents, or, rather, I am not prepared to report any results from them. We take any paints as they come into the laboratory and we are slowly collecting and correlating results.

In the case of pitting of white lead, I think our experiments indicate rather clearly that the trouble is in the oil rather than in the pigment. There are some experiments on treating the oil with samples of pigment, and then using that oil with fresh pigment, which I think indicate rather conclusively that the trouble is in the oil itself.

ACCELERATED WEATHERING OF PAINTS ON WOOD AND METAL SURFACES.[1]

BY HARLEY A. NELSON.[2]

The most universal weathering cycle responsible for the deterioration of exposed surfaces is light, moisture, and temperature variations. Other weathering agents, such as wind and abrasive dust, are more localized. Any scheme for accelerated weathering must, in so far as possible, seek a practical working combination of the components of this cycle.

Accelerated tests have been proposed[3] which follow changes in some particular physical property of the paint film. This paper describes an effort to reproduce directly on typical surfaces, not only changes in some one physical property, but all of the more common paint failures that are observed on painted wood and metal structures. With this objective, it has been necessary to study and develop the most available artificial sources for light, moisture and temperature variations.

DEVELOPMENT OF APPARATUS.

Description of Equipment.—An exposure tank (Fig. 1) has been constructed to facilitate simulation of a variation of possible weathering conditions. This tank is of wood with an insulating air space and galvanized iron lining. The cover is provided with a 10-in. opening, which receives a removable collar *B* supporting a quartz mercury arc *A* of 30-in. effective lighting length. The test panels *C* are supported by zinc nails on removable racks provided with sheet-zinc water drains. Water simulating a beating rain is provided by a revolving spray *D*, and fine fog or mist by the atomizer *E*. An ordinary variable-speed electric fan serves to cool the mercury arc and maintain a uniform temperature. Fig. 2 is a general photographic view of this apparatus with the cover raised, showing the quartz mercury arc in place and the arrangement of the panels in the removable racks.

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[1] A contribution from the Research Laboratory of the New Jersey Zinc Co.

[2] Research Laboratory, New Jersey Zinc Co., Palmerton, Pa.

[3] A. M. Muckenfuss, "Accelerated Test for Paint and Varnishes," *Journal Industrial and Engineering Chemistry*, July, 1913;

H. A. Gardner, "Paint Technology and Tests," (1911);

H. A. Gardner, "Physical Testing of Paint and Varnish," *Circular No. 122*, Educational Bureau, Paint Mfgrs. Assoc. of U. S.

Source of Ultra-Violet Light.—Any accelerated test on paints depends on adequate radiations in the ultra-violet region of the spectrum. The magnitude of the effect of ultra-violet light on the physical properties of oxidizing films has been indicated in a previous paper.[1] Very pronounced chalking was then reproduced by artificial means on a film of 100-per-cent basic carbonate white lead in raw linseed oil, after an exposure of 13 hours at 8 in. from a small laboratory mercury arc. This indicated that with a sufficiently intense source of ultra-violet energy, these results might be reproduced on a larger and more practical scale. A quartz mercury arc of 30-in. effective radiating length was finally developed.[2] This arc is used on 220-240 volts D. C., and normally draws 6 to 7 amperes when the atmosphere within the exposure tank is maintained at 50 to 60° C.

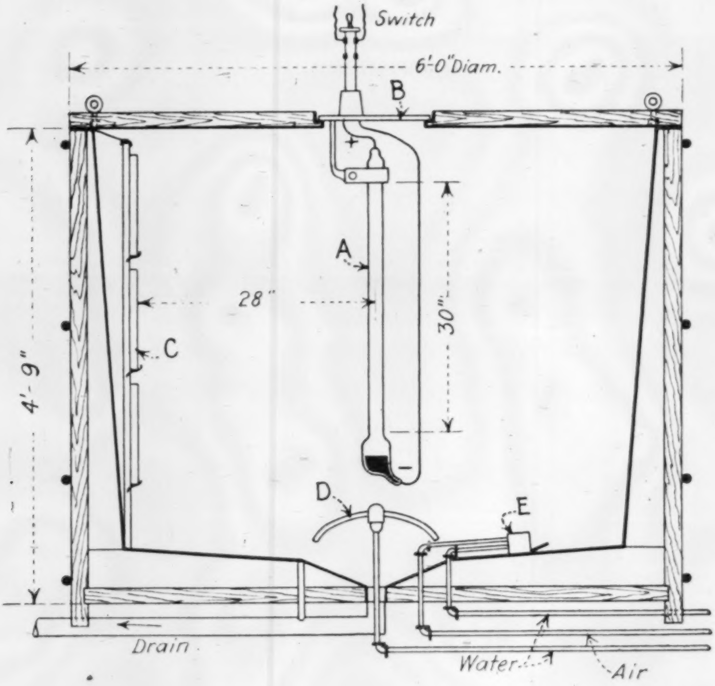

FIG. 1.—Cross-Section of Exposure Apparatus.

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[1] H. A. Nelson, "Stress-Strain Measurements on Films of Drying Oils, Paints and Varnishes," *Proceedings*, Am. Soc. Test. Mats., Vol. 21, p. 1111 (1921).

[2] By the Engineering Division of the Cooper-Hewitt Electric Co.

Relative Intensity of Mercury Arc in Ultra-Violet.—The straight line curve in Fig. 3 (upper half) shows the relative distribution of the energy of the sun's spectrum in the blue and the ultra-violet (wave lengths λ from about 4500 to 2900 Ångstrom units), while the columns indicate the relative intensities of the more important groups of lines of the mercury arc spectrum.[1] According to this, the mercury arc is especially strong just where the sun's spectrum, due to absorption of the shorter wave lengths, falls off to practically nothing. This absorption by the earth's atmosphere is so great that Fabrey and Buisson[2] report that only one-millionth of the energy possessed by a short wave

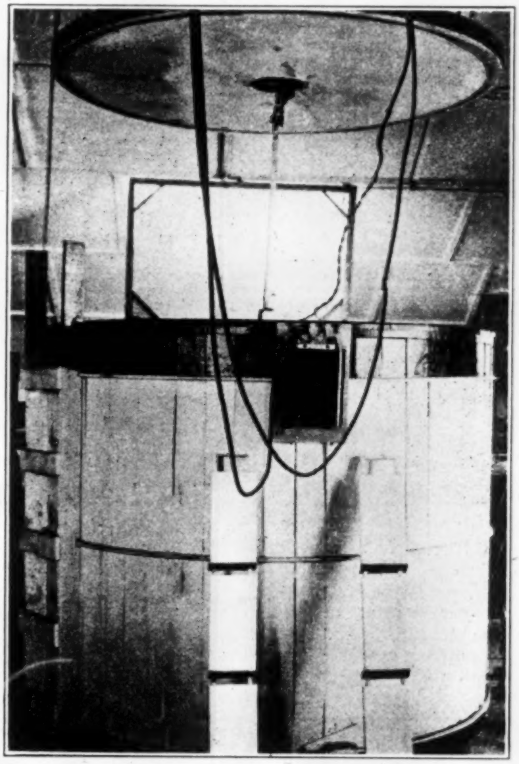

FIG. 2.—Exposure Tank with Cover Raised Showing Quartz Mercury Arc in Place. Panels in Removable Racks Shown in Foreground.

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[1] F. W. Aston, "Report on the Action of Sunlight on Aeroplane Fabric," T. 1019 British Advisory Committee for Aeronautics (1917).

[2] *Jour. de Phys. et le Radium*, July, 1921.

length at the upper confines of the atmosphere finally reaches the earth. Coblentz[1] found that the region below λ = 4500 Å.U. represents about 5 per cent of the sun's total radiation energy, whereas for

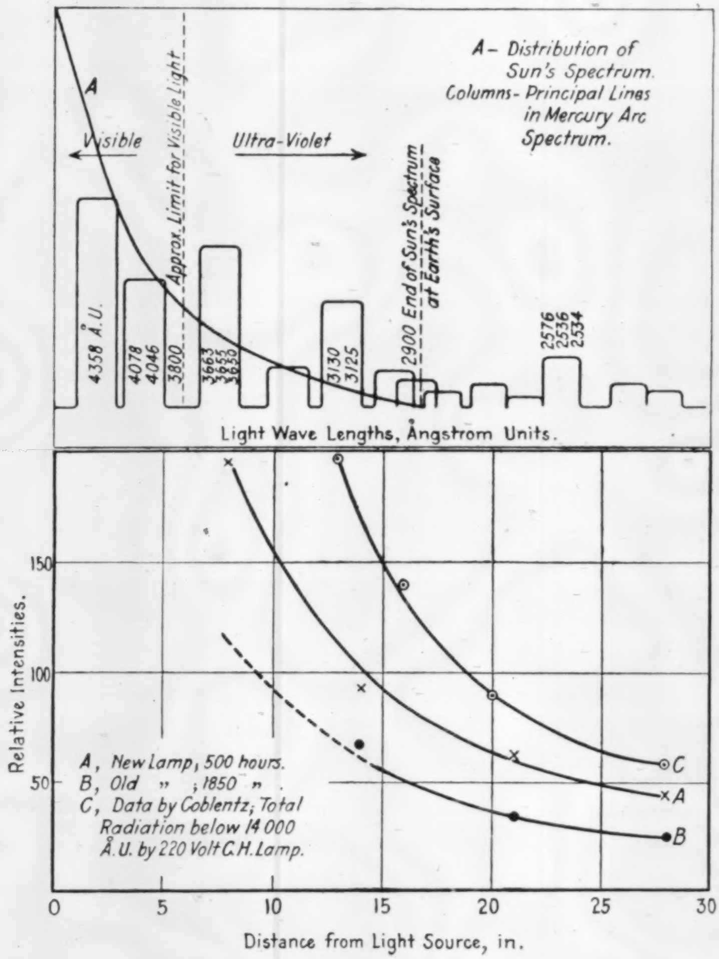

FIG. 3.—*Upper Half.*—Relative distribution of energy from ultra-violet portion of sun's spectrum and relative intensities of principal groups of lines in the mercury arc spectrum.

Lower Half.—Relative intensities of ultra-violet energy from region of $\lambda = 3000$ Å.U. and below, for old and new quartz mercury arcs.

the quartz mercury arc this region represents about 20 per cent of the total energy.

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[1] *Scientific Paper No. 33*, U. S. Bureau of Standards.

Life of Quartz Mercury Arcs.—It is most important that something be known about the rate of deterioration of the quartz tubes, that is, the amount of the ultra-violet radiation cut off by the clouding of the quartz. This clouding is ascribed both to decomposition products from the electrodes and to changes in the nature of the quartz. Coblentz[1] finds that the percentage of the total radiation which is below λ = 4500 Å.U. decreases from an initial value of 70 per cent to about 50 per cent after burning 1000 to 1500 hours. It should be noted (see Fig. 3) that this includes the strong groups of lines at λ = 4360 and λ = 4060 Å.U., which are not, as we shall see later, sufficiently active to cause perceptibly accelerated deterioration of paint films.

Aston[2] reports that a photograph of the mercury arc spectrum taken through the quartz of a burner which has been in use for 200 hours showed almost complete obliteration of all the lines in the ultra-violet, except the ones at λ = 3660 Å.U. and λ = 3130 Å.U. However, none of the observations made during the present tests would indicate a loss of effectiveness of the burners comparable with this until after 1000 to 1500 hours of service.

A quartz spectrograph has not been available for these experiments, but advantage has been taken of the ionization of a zinc plate in vacuum by energy of wave lengths in the region of λ = 3000 Å.U. and below, to discharge a gold leaf electroscope.[3] The rate of discharge for the electroscope increases with the intensity of the ultra-violet radiations and, by deducting the normal (dark) leak discharge, the relative intensities of the radiations are calculated as follows:

$$\frac{i_1}{i_2} = \frac{\frac{1}{t_1} - \frac{1}{t_0}}{\frac{1}{t_2} - \frac{1}{t_0}},$$

where

t_1 = time (seconds) to discharge electroscope under burner No. 1,
t_2 = time (seconds) under burner No. 2,
t_0 = time (seconds) to discharge when ultra-violet radiations are cut off by glass screen (dark leak),
i_1 = intensity of burner No. 1, and
i_2 = intensity of burner No. 2.

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[1] *Scientific Paper No. 33*, U. S. Bureau of Standards.

[2] F. W. Aston, "Report on the Action of Sunlight on Aeroplane Fabric," T. 1019 British Advisory Committee for Aeronautics (1917).

[3] The author is indebted to A. H. Pfund, Johns Hopkins University, for suggesting that the ionizing properties of zinc under ultra-violet radiations might be used for this purpose.

Curves *A* and *B* of Fig. 3 (lower half) show values obtained in this manner for two burners. Burner *A* had been in use for 500 hours and, within the accuracy of the observations, had lost none of its effectiveness on paints. Burner *B* was first used for 1600 hours, at which time its effectiveness had decreased very markedly. The deposit on the surface of the quartz was then removed in so far as possible by heating strongly with a blast (this treatment does not clear away all of the deposit) after which the tube was put back in service for 250 hours, making a total of 1850 hours. The relative intensities of the two burners in the ultra-violet region ($\lambda = 3100$ Å.U. and below) are then in the proportion of 1.7 to 1 when used at 220-240 volts and 6.5 amperes, indicating a decrease of about 40 per cent for the old burner. Curve *C* is one given by Coblentz[1] for the intensity of the total radiation below $\lambda = 14{,}000$ Å.U., from a 220-volt Cooper-Hewitt quartz burner. It is not comparable with curves *A* and *B*, but illustrates the similarity of the intensity curves.

Effective Wave Lengths.—That the wave lengths which act destructively on the oxidizing oil binder of paints are below $\lambda = 3660$ Å.U. was demonstrated by exposures on paints for about 400 hours to the radiations from a crown glass mercury arc transmitting about 90 per cent of the radiations at $\lambda = 3600$ Å.U. and about 50 per cent at $\lambda = 3300$Å.U. In this time the only destructive light effect observed was a loss of gloss, such as would ordinarily appear after about 10 to 15 hours under the quartz mercury arc. If the rapid deterioration of the ultra-violet transmission of quartz tubes observed by Aston[2] is representative, few of the wave lengths beyond $\lambda = 2900$ Å.U., except possibly those at $\lambda = 2534$–2576 Å.U., persist for any length of time. The fact that quartz tubes used as long as 1000 hours are still very destructive suggests that the group of lines near $\lambda = 3100$ Å.U., and those ranging at and just below λ 2900 Å.U. (see Fig. 3), are the ones largely responsible for the deterioration of oxidizing oil films.

Aston[2] concludes that the deterioration of linen fabric under sunlight is due to ozone formed in or on the fiber. The formation of ozone in air requires radiations of less than $\lambda = 1850$ Å.U., which never reach the earth's surface. However, for oxygen absorbed in the fiber, he has calculated indirectly that the most powerful ionizing wave length should be $\lambda = 3230$ Å.U., a value which agreed fairly closely with the wave lengths found by experiment to be very destructive. Similar calculations have been made (by the author) for linseed oil, the results of which give a figure near λ = 3000 Å.U. for the wave lengths which might ionize absorbed oxygen to ozone. Whether the mechanism whereby the oxidation and final destruction of linseed oil is promoted by light is ionization of absorbed oxygen, or whether it is a case of polymerization alone, remains to be determined experimentally.

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[1] *Scientific Paper No. 55*, U. S. Bureau of Standards.

[2] F. W. Aston, "Report on the Action of Sunlight on Aeroplane Fabric," T. 1019 British Advisory Committee for Aeronautics (1917).

Moisture.—The water spray (*D*, Fig. 1) is primarily intended to function as a washing or abrasive medium to remove loose "chalk," and the water must be applied under considerable pressure. Difficulty was at first experienced with an iron deposit from the ordinary tap water used, but it was later learned that this could be largely eliminated by greatly increasing the washing force of the water stream.

The saturation of the film proved to be important as a factor in the deterioration aside from the abrasive action of the water stream. The water absorbing properties of ordinary paint films are normally very great, decreasing as the linoxyn content of the film increases.[1] Under any condition, the film is sensitive to the degree of saturation of the surrounding atmosphere, and the atomizer (*E*, Fig. 1) is provided to guarantee a saturated atmosphere if it is desired.

Temperature and Temperature Variations.—The maximum temperature permitted is 60° C. (140° F.), which is maintained and regulated by the heat from the mercury arc and the volume of air circulated within the tank. During the winter months low temperatures were attained by periodic outdoor exposures. No really satisfactory means for attaining low temperatures during warm weather have been developed, since the temperatures attained in an ice box did not show marked acceleration of expansion and contraction effects. Convenient means for suddenly varying the exposure temperatures over the effective range are still to be developed.

APPLICATION OF TEST EXPOSURES.

Choice of Exposure Cycle.—Obviously, it is impossible to follow the natural weathering cycle at every turn. Simplicity for routine application and observation is a factor which makes the 24-hour cycle convenient and desirable. Twenty-four hours of light (temperature 50 to 60° C.), 24 hours of low temperature, 24 hours of water spray, followed again by 24 hours of light, etc., is a cycle which embodies the elements of simplicity and severity. However, this has not been entirely practicable during the summer months. The difficulties attending refrigeration at sufficiently low temperatures led to further modification of the exposure cycle to 24 hours of light (50 to 60° C.), cooling rapidly to the lowest available temperature, followed by 24 hours of water spray, etc.

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[1] Morrell, *Journal*, Oil and Color Chemists' Assoc., October, 1921.

Panels Used.—The wood panels are 6 by 12 by $\frac{3}{4}$ in., finished on all sides, and painted with three coats of the test paint according to standard practice, or otherwise, as desired. The wood must be carefully chosen from well-seasoned, sap-free material. White pine has been used almost exclusively and, if carefully selected, proves very satisfactory. Room is provided for about 75 panels, which permits tests being made in duplicate or triplicate.

TABLE I.—LOSS OF GLOSS AND CHALKING ON PAINTS.

Exposure Cycle: 24 hours light—cool—24 hours water spray.

Pigment.	Percentage of Vehicle.	Total Days Exposure Required for	
		Complete Loss of Gloss.	Initial Chalking.
100 per cent XX (Lead Free) Zinc Oxide	50	14 (16 – 20)[a]	16
100 per cent Leaded (35 per cent) Zinc Oxide	40	9 (10 – 12)	12 (13 – 15)
100 per cent Light Resistant Lithopone	40	4 (3 – 5)	6 (5 – 6)
100 per cent Basic Carbonate White Lead	30	3 (3 – 4)	5 (5 – 6)
100 per cent Titanox (BXX)	30	2 (3 – 4)	4 (5 – 6)
40 per cent Zinc Oxide (Lead Free) 40 per cent Lithopone 20 per cent Whiting	45	9	11

[a] Figures in parenthesis represent observed number of months required on outdoor exposures.

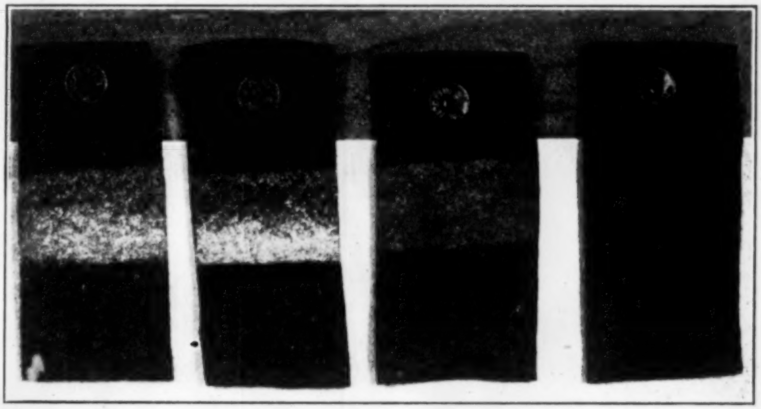
Steel panels have been used 6 by 12 by $\frac{1}{16}$ in., made up from some standard grade material. The paints have usually been applied in sections of one and two coats, with the two-coat application on the upper one-half.

Exposure Distance.—The distance from the panels to the light source (see Fig. 1) is 28 in., which was arbitrarily selected before relative intensity measurements were available for the lamps to be used. The object then was to maintain a high test-panel capacity without sacrificing too greatly the light intensity, and also to permit the panels to be properly reached by the revolving spray. Reference to Fig. 3, curves *A* and *B*, shows that very little is to be gained in ultra-violet intensity by cutting down the exposure distance without also very materially cutting down the testing capacity of the apparatus.

Time of Exposures.—Exposures have usually been inaugurated with 24 hours' exposure to light, thus giving the paints full benefit of thorough drying. Inspections have been made each day, or whenever the tests demanded. It was hoped that results might be attained within at least 30 days, but exposures of 80 to 90 days, or even longer, were found necessary, depending on the results being sought. The reproduction of cracking, for example, requires prolonged exposures with the present equipment.

RESULTS FROM TEST EXPOSURES.

The panels are closely inspected for evidence of typical paint failures, such as loss of gloss, chalking, flaking, checking, cracking, scaling, peeling, separation of coats and lack of adherence to surface (with formation of blisters), discolorations, fading and washing of tints, and, in the case of paints on iron, first evidence of corrosion. The extent to which each of these has been produced will be considered.



(*a*) (*b*) (*c*) (*d*)

(*a*) 100 per cent basic carbonate white lead.
(*b*) 100 per cent light-resistant lithopone.
(*c*) 40 per cent XX zinc oxide, 40 per cent lithopone, 20 per cent whiting.
(*d*) 100 per cent XX (Lead Free) zinc oxide.

FIG. 4.—Relative Amounts of Removable Chalk on White Paints After Exposure of 480 Hours.
(Trace of "chalk" from zinc oxide not shown by photograph.)

Loss of Gloss and Chalking.—Chalking follows the progress of loss of gloss so closely that these may be considered together. Table I gives results on a series of paints made up with raw linseed oil (88 per cent) turpentine (7 per cent), and liquid drier (5 per cent).

Fig. 4 further illustrates graphically the relative amounts of "chalk" removed from painted wood panels in drawing a black cloth once across the surface at the end of 480 hours' exposure, as described in Table II.

The effect of moisture absorbed by the film is very evident in promoting loss of gloss and "chalking" upon exposure to light. How the light energy requirements are reduced under these conditions is demonstrated by Table II.

The mechanism of this acceleration has not been investigated, but the fact that water carries with it dissolved oxygen in very appreciable amounts suggests that activation of this additional oxygen through ionization may be responsible. Certainly, these results agree with the observed tendency of certain paints to "chalk" excessively when exposed in localities where periods of hot sunshine follow saturating rains and are accompanied by a very high relative humidity.

TABLE II.—EFFECT OF PERIODIC SATURATION OF FILM AND MAINTENANCE OF A SATURATED ATMOSPHERE DURING EXPOSURE ON THE RATE OF DETERIORATION.

Paint.	Complete Loss of Gloss.		Time Required for First Appearance of "Chalk."	
	Days Light Required Dry.	Days Light Required Saturated.	Days Light Required Dry.	Days Light Required Saturated.
100 per cent XX (Lead Free) Zinc Oxide, Raw Linseed Oil	9	6	12[a]	8[a]
100 per cent Basic Carbonate White Lead, Raw Linseed Oil	3	2	5	3

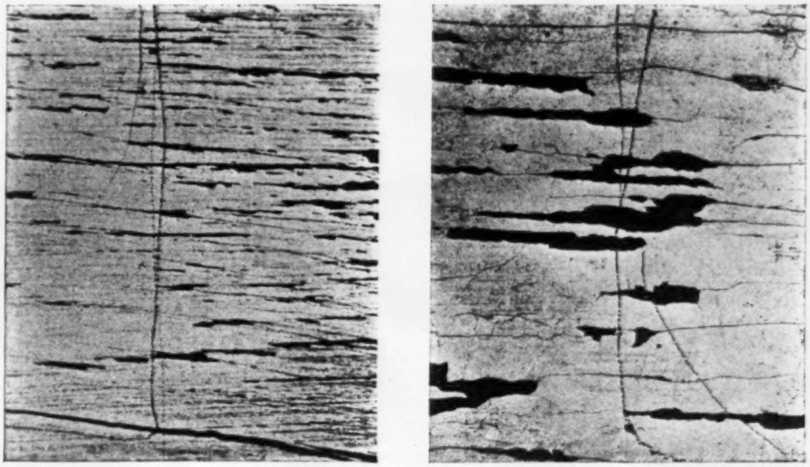
[a] "Chalking" on the Zinc Oxide films is superficial only, and does not develop progressively beyond this stage.

Freezing saturated films has been observed to very definitely promote the formation of removable "chalk." Undoubtedly, this is due to expansion effects, possibly of ice formed within the film, which destroy the anchorage of the already partially loosened pigment particles.

Flaking.—No failure of this nature has yet been observed.

Checking.—The fine hair-line "checking" that finally develops into deep checking and cracks to the surface, has not been reproduced.

Cracking, Scaling, Peeling.—The effective exposure cycle for producing cracking is one including 24 hours exposure to outdoor winter temperatures, ranging from −5 to −18° C. (23 to 0.0° F.). Exposure of the saturated films developed fine hair-line cracks, mostly longitudinal with the grain of the wood, which later broke across and, upon further wetting and freezing, developed into scaling. On the other hand, exposure to low temperatures just after exposure to light (dry film) brought about a more widely spaced cracking developing into peeling. The difference in the nature of the results obtained on one particular paint under such circumstances is illustrated by the photographs shown as Fig. 5. *A* has been exposed to freezing temperatures after each period of saturation, while *B* has been exposed to freezing temperatures following each exposure to light at 50 to 60° C. The exposure time was a total of 100 days, divided roughly into periods of one-third each of light, low temperature and water spray. About 80 days were required for first evidence of cracking. This particular paint is one which, on the test fence, developed considerable cracking and scaling in a period of 14 to 15 months.



(*a*) Cracking and scaling on paint exposed to freezing temperatures after being saturated with moisture.

(*b*) Cracking and peeling on paint exposed to freezing temperatures after hot, dry exposures.

FIG. 5.

Accelerated reproduction of cracking doubtless depends upon periodic exposures to temperatures considerably below freezing, but once cracking has developed, scaling and peeling follow rapidly under the influence of the repeated wetting and rapid drying.

Lack of Adherence.—Lack of adherence is, more strictly speaking, a painting rather than a paint defect. Cases of very marked separation of the upper coats from the primer, or of the entire film from the surface, have been evidenced by the formation of blisters when the saturated films are exposed to the heat (50 to 60° C.) of the mercury arc. Theoretically each panel has been painted under ideal conditions. Discounting possible painting defects, these failures may be ascribed to hardness or low permeability of the film, which retards the passage of moisture from within and builds up sufficient pressure to release the film at places where the adherence is least perfect.

Discoloration of White Pigments.—Certain white pigments are discolored by the ultra-violet radiations from sunlight. The common lithopones are most susceptible, and certain white leads have also given evidence of surface darkening. However, a light-resistant lithopone has been tested in white paints up to three years on exterior exposures, without any sign of darkening. The exposure to the mercury arc brings to bear a concentration of ultra-violet radiations under which even this lithopone cannot hold its color permanently, and certain white leads blacken decidedly.

TABLE III.—TESTS OF PAINTS ON IRON.

Exposure Cycle: 24 hours Light—24 hours Moisture.

Paint.	Pigment Analysis.	Percentage of Vehicle.	Percentage Volatile in Vehicle.	Days Exposure for		Condition at End of 84 Days.
				Loss of Gloss.	First Appearance of Rust.	
495 Red	83 per cent Fe_2O_3 .... 15 " Zinc Oxide (Raw Linseed Oil). .	55	15	16	75	Very slight rusting. Very heavy chalking. Very slight fading.
496	100 per cent Red Lead . . .	23	10	9	80	Very slight rusting. Very heavy chalking. Faded to light orange yellow.
460 Red	42 per cent Fe_2O_3 .... 54 " Clay	50	20	4	65	Slight rusting. Slight chalking. Slightly faded.
472 473 Red	33 per cent Fe_2O_3 .... 36 " Clay......... 25 " Gypsum.....	50	20	2	60	Considerable rusting. Heavy chalking. Considerably faded.
477 478 Red	56 per cent Fe_2O_3 .... 28 " Asbestine.... 10 " Whiting..... 5 " Gypsum.....	50	40	4	40	Considerable rusting. Considerable chalking. Slightly faded.
489 490 Red	28 per cent Fe_2O_3 .... 40 " Asbestine.... 27 " Barytes......	50	38	5	36	Badly rusted. Considerable chalking. Slightly faded.
481 Red	80 per cent Fe_2O_3 .... 10 " Asbestine.... 5 " Silex........ 5 " Whiting......	49	40	4	44	Very badly rusted. Considerable chalking. Very slightly faded.
467 468 Red	27 per cent Fe_2O_3 .... 12 " Silex......... 29 " Whiting..... 29 " Gypsum.....	50	31	2	29	Very badly rusted. Heavy chalking. Considerably faded.
462 Grey	50 per cent ZnO......... 20 " Sublimed Lead...... 25 " Silicates..... 5 " Whiting......	45	20	4	35	Slight rusting. Considerable chalking. Very slightly faded.

The relative action of the common and light-resistant lithopones is worthy of note. During the first period (of 24 hours under the mercury arc, with a saturated atmosphere) the common lithopones darken decidedly in 1 to 5 hours, while the light-resistant material remains unaffected. During the second day (24 hours water spray) the common lithopones regain their color. The following ultra-violet exposure (24 hours) on the saturated panels may cause a slight darkening of the light-resistant lithopone, while the common material will redarken completely. Alternate fading and redarkening follow, finally resulting in a permanent yellowing, which becomes appreciable in 3 to 5 days on a common lithopone, and in 10 to 14 days on the light-resistant material.

The darkening of white lead has not been investigated at any length, but it apparently varies with the source of the white lead. It differs from lithopones in that there is no recovery of original color when the mercury arc is removed. The dark reaction product is superficial and the original color may be exposed by removing the surface "chalk."

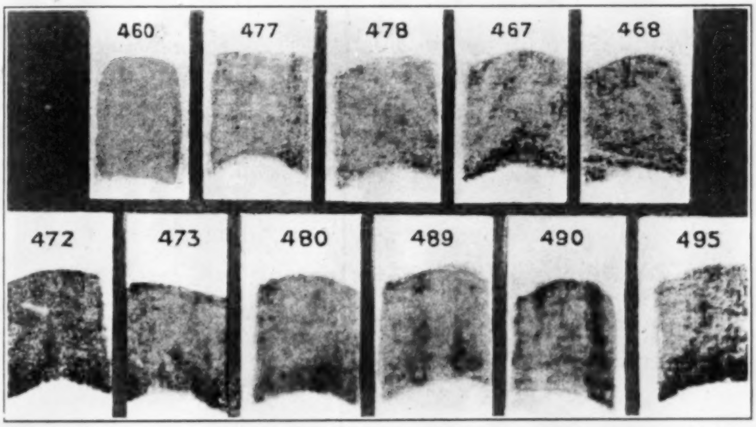


FIG. 6.—Relative Amounts of Removable Chalk on Painted Steel Panels. 84 Days Exposure. See Table III.

As with "chalking," the rates at which these discolorations take place are accelerated by the presence of moisture in the exposed film.

Fading of Tints.—Tinted paints may fade for two reasons. Disintegration of the surface through "chalking" may expose the pigment to the air, with the result that the difference in the refractive index ratios of pigment-air and pigment-linoxyn causes an apparent change in color; or the coloring material itself (especially if a lake color) may be reacted upon by light and moisture. A film which chalks excessively soon shows a faded appearance, which is further aggravated if the color reacts under light. Mixed colors, as for example, greens made from Prussian blue and chrome yellow, are easily and quickly distinguished from pure colors, such as chrome green.

Paints on Metal Surfaces.—The more simple exposure cycle (24 hours light, 24 hours water spray) has been effective in hastening the deterioration of paints on metal. Attempts have been made by others to apply the salt-spray test, as used on galvanized and other metal-protected iron, to paints on metal. This is illogical since it ignores the normally increasing water resistance of the film with each increase of its linoxyn content.[1] A combination of the salt-spray test with ultraviolet exposures would be more logical.

Table III summarizes results from representative exposures of a number of paints submitted by paint manufacturers for ordinary industrial use.

Fig. 6 will illustrate the relative amounts of removable chalk on the surfaces of the red paints referred to in Table III.

Unfortunately, the outdoor test exposures on this series of paints have not been in place sufficiently long to permit direct comparison of results. But careful consideration of these results in the light of industrial experience, and the nature of the formulas represented, leads to the conclusion that the apparent order of merit is generally as would be expected.

CONCLUSION.

The application of accelerated tests as a criterion of service quality in the development of a product of industry has been the source of much discussion pro and con. That there exists a general need for such tests, wherever changes with time are an indication of quality, there can be no question. But no test of this kind can take its place as an instrument in the hands of industry without itself passing the test of time. The present limitations of the test just considered must be recognized. It is a mark of progress, at the present stage of development, to know that at least some of the physical changes that characterize such a very complicated thing as the weathering of a paint on exposed surfaces, can be reproduced on an accelerated scale. This partial success gives hope of a final, more complete simulation of natural weathering.

In concluding, the author wishes to express his appreciation for the many helpful criticisms and suggestions received from other members of our Research Department.

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[1] Morrell, *Journal*, Oil and Color Chemists' Assoc., October, 1921.

DISCUSSION.

Mr. P. H. Walker.—I should like to ask a question. I am wondering, considering the great parallelism that Mr. Nelson gets between the long exposure to the sun and this short accelerated exposure to ultra-violet light, whether the slight dimming of the ultra-violet light does not very soon cut off the very short lengths that do not appear in the sun spectrum. **Mr. Walker.**

Mr. E. C. Holton.—I should like to ask if there is any ozone formed in the cabinet. It is well known that ozone has a very powerful action on many organic compounds and if there is much ozone developed in the cabinet the destruction of the paint film is probably due more to the ozone than to the ultra-violet rays. **Mr. Holton.**

Mr. H. E. Smith.—Judging from the remarks on the change in the gloss, I assume that the experiments must be comparative, as all the panels were tried at the same time and during the same period, as far as the paint lasts. Could one panel be tried now and another one a few months later and then be compared fairly? **Mr. Smith.**

Mr. R. L. Hallett.—It certainly is a very interesting paper and describes the development of an ingenious piece of apparatus. I note several statements in the conclusion, and among them the following: "But no test of this kind can take its place as an instrument in the hands of industry without itself passing the test of time. The present limitations of the test just considered must be recognized." This, of course, is true, and while a large amount of very interesting experimental work has been done, the paper contains several statements which would seem to indicate that the conditions under which these tests were made are not exactly comparable to the ordinary weathering of paint exposed to the elements of nature. On page 487 the statement is made: "According to this, the mercury arc is especially strong just where the sun's spectrum, due to absorption of the shorter wave lengths, falls off to practically nothing." In other words, the lamp gives off rays which are supposed to be much more harmful to a paint film than the rays from the sun which penetrate the earth's atmosphere down to the surface of the earth, and, therefore, the rays given off by this lamp might produce results quite different from anything possible with sunlight, even after the most prolonged exposure to the direct rays of the sun. Then again, in Table I, is given the length of time for the loss of gloss and initial chalking for various paints. The table shows the time for paints made with various pig- **Mr. Hallett.**

Mr. Hallett. ments, among which is light-resistant lithopone, and the figures given for light-resistant lithopone show a length of time for loss of gloss and chalking greater than the time required for several other pigments of known great durability. I can hardly reconcile those results with practical tests. For instance, last year at our paint testing farm at Sayville, L. I., we put out a paint made with light-resistant lithopone, linseed oil, turpentine and drier—I suppose either the same or approximately the same lithopone as is referred to in this paper—and within a few months the paint lost its gloss and began to chalk. At the end of twelve months the paint was entirely gone from the panel on which it was applied. Now, if in practice that paint could be entirely removed from the panel in one year by the simple action of the natural elements, and if in the test described in this paper the same paint appears to stand up as well or better than other paints which were exposed at Sayville at the same time and show almost a perfect condition at the end of the year, it perhaps should make us hesitate in accepting tests of this kind as being indicative of the results which might be expected when paints are exposed under ordinary weather conditions in regular painting practice.

Mr. C. H. Hall. MR. C. H. HALL.—The great advantage of an accelerated method of testing paint cannot be exaggerated. We all realize the great importance of being able to bring about these results in a short period of time, and I think the results of this paper are most interesting and most important. The fact must be borne in mind, however, that the method of testing is unbalanced. In other words, one element which leads to destruction, that of light, has been accelerated very greatly, but the other elements, which are probably equally as important, have not been accelerated but probably are not equal to those of nature. Temperature changes and various other things that occur in nature have probably not been equaled, consequently you have an unbalanced condition and that unbalanced condition is, no doubt, what would bring about a condition commented on by Mr. Hallett. The question of the action of oxygen and moisture is dependent on the time factor in bringing out certain chemical changes.

Mr. Muckenfuss. MR. A. M. MUCKENFUSS.—I am extremely interested in this work on account of a similar investigation I conducted several years ago. I want to say here that judging by my experience, the greatest difficulty to be had in producing artificial weather is in the ability to vary rapidly the humidity conditions, that is to say, to go from a condition of extreme moisture to extreme dryness as regards the paint film inside the testing box, even as rapidly as occurs often in weather changes. I think therefore that one of the greatest difficulties will be in getting the changes of humidity in the film sufficiently rapid.

Mr. Breyer. MR. F. G. BREYER.—I should like to make one remark in connection with Mr. Hallett's statement, and that is, that we are very definitely aware of the fact that we haven't accelerated other conditions than light, but what we set out to do was this: The average life of a paint on the side that is not exposed to the severest sun conditions is some two or three years longer than it is on the side exposed to the light. We didn't want to bite off too much and say that we were going to make a paint last forever and try to overcome all the objections. We simply said that if we can determine the things that cause the destruction of paint upon the south side, the side exposed to the sun, we will at least have made a diagnosis and analysis of the first limiting factor in paint life to-day. If we can get paints to last as long on the south side as they do on the north, we have increased the average life of the job some two or three years.

Mr. Busby. MR. H. S. BUSBY.—It is important to isolate the other variables from that one variable of light exposure. The important thing beyond that, however, is that a test made with ultra-violet radiation is not comparable to a test made with radiation which is the equivalent of the visible region of the solar spectrum. We have found in tests with pigments and dye stuffs that there is no qualitative relation between the results. We would go so far as to say that in some cases a directly opposite result was obtained with violet radiation from what is obtained with the solar radiation. Until some method can be found to determine, comparatively, point by point, the ratio between the different regions of the visible spectrum and the ultra-violet region no such data as described in these tests are of dependable value. To date, the literature contains no qualitative or quantitative data of any such ratio.

Mr. Nelson. MR. H. A. NELSON.—There is some difference of opinion, and very little data so far, on the question as to what radiations are cut off by the clouding of the quartz and when, but these quartz burners are very effective even after they become perceptibly clouded, and certainly nothing below $\lambda = 2500$ ÅU. gets through at that stage. How much more clouding is required to cut off radiations in the region above $\lambda = 2500$ ÅU. we do not yet know although we expect to find out. One thing I might emphasize—it is brought out in the paper—is the fact that we exposed paints to the radiations from a crown glass mercury arc for several hundred hours and were able to obtain only a slight loss of gloss. Now this glass transmits over 50 per cent of the radiations down as far as $\lambda = 3300$ ÅU., which shows definitely that the really effective radiations lie below this region. Whatever these effective radiations are, they are very persistent.

Mr. Nelson. The burners do not lose their effectiveness to a marked degree until after prolonged use, when the clouding of the quartz is also very marked.

I am very much interested in Mr. Busby's statements, because we have not been able to locate any definite data on comparisons of the effects of sunlight and the mercury arc on dyes. However, it has been suggested by Mr. Pfund that any lack of agreement in exposures on dyes might be due to the absence of certain radiations in the mercury arc spectrum which are highly absorbed by the dye being tested. These radiations being present in the sun's spectrum, the exposure results might not agree. I might go on to state that according to results presented by Mr. Goldsmith in connection with Mr. Aston's reports (referred to in the paper) a film of linseed oil varnish shows no selective absorption of radiations from the ultra-violet region of the sun's spectrum, and absorbs the mercury arc spectrum apparently uniformly up to about $\lambda = 3126$ ÅU. This would indicate that for linseed oil no differences in the action (except of rate) of the sun and the mercury arc are to be expected. Moreover, we have already seen that the effects of the exposures are in fair agreement as to the nature of the results actually obtained. But I quite agree with Mr. Busby that the matter deserves careful checking as soon as the means for doing so are available.

Ozone is formed in the apparatus, but constant circulation of fresh air must be maintained to cool the mercury arc, and it is doubtful if sufficient ozone can accumulate to affect the oxidation of the paint films.

In reply to Mr. Hallet's criticism, we have observed the same things that Mr. Hallett has observed about the lasting qualities of straight lithopone paints with raw linseed oil. Nevertheless, we find that it does require some time, and a surprisingly long time, for them to lose their gloss and begin chalking, while the disintegration goes on rapidly after that point has been passed. The thing to be emphasized is the fact that in so far as loss of gloss and chalking are concerned, the results by this method do show a fair agreement with outdoor exposures in our section of Pennsylvania.

Mr. Holton. MR. HOLTON.—Some years ago Mr. W. R. Mott, of the National Carbon Co., did considerable work on the white flaming arc, and it seems to me that the light from the white flaming arc is more nearly comparable to sunlight in its effect than this light.

Mr. Nelson. MR. NELSON.—We gave the white flaming arc very serious consideration but found that its use presented certain difficulties, the principal one being lack of uniform intensity over any wide area such as we wanted. The 30-in. quartz tube does well in this respect.

Mr. Bingham.

MR. E. C. BINGHAM.—It has seemed to be implied that the south side of a building differed from the north side mainly in the light exposure, but I have noticed that the shrubbery on the south side of a building is often winter-killed, whereas that on the north side of the house is not winter-killed. That can't be due to ultra-violet light. It is generally attributed to the difference of temperature which is brought about by the sunlight, and it seems to me that it will be quite interesting to bring about those changes of temperature.

AN ANALYSIS AND COMPARISON OF SYSTEMS OF COLOR MEASUREMENT; A PROPOSED ARRANGEMENT FOR MEASURED COLORS; AND SOME SOME NOTES ON INTERCHANGEABILITY IN COLOR MEASUREMENT.

By H. S. Busby.

Nature and Development of Color Systems.

The development and construction of color systems has been an evolution. Although it may truly be said that this has been partly due to the fact that in the very beginnings of applied physical science not enough was known of the nature of the laws of optics and color to arrange or even properly measure any group of colored materials, nevertheless the true reasons for the growth of such systems lay in the need, which developed, for commercial application of them, once they could be delineated.

These needs were fourfold:

1. To specify, that is, to describe accurately, in any consistent intelligible terms, a color, so that it could be distinguished from another.
2. To measure degrees of color difference, and assign, or determine, steps between the two so that one color could be described as having x steps more red than another or as being y steps darker than it.
3. To record any color by a notation expressive of its appearance.
4. To record, in imperishable standards and notation, any color that has been measured, so that this record might be referred to, and the color revisualized and recreated therefrom, no matter if the original samples were lost or marred.

A later stage of the evolution was the requirement that colors be so analyzed or studied that it would be possible, from this analysis, to study in detail the fundamental laws governing their relation, also the relation, if any, between the color measurement and the mixture (in quantities of material) required to produce the color.

Types of Color Analysis and Arrangement.

All the methods of color measurement and systems of combining them may be classed under four general headings:

1. *Methods for Comparison Only of Colors.*—These are in no sense methods of measurement. They have no units of comparison, and frequently no calibration of their performance. They are simply the laboratory arrangements that have been found to be convenient means of determining whether or not two colors match. In this class may be listed such devices as the Lummer-Brodhun cube, reducing shutters, bright-spot-screen photometers, filters, comparison solutions, devices for mixing colored lights, sliding bench arrangements, etc.

2. *Methods of Measurement in Terms of Some System of Arbitrary Units.*—This second group displays the intent to measure color, and it includes, by far, most of the colorimeters produced to date. Its primary condition is that its units of measure need only be repeatable, for later reference. In this group are photometers whose performance is based upon calibrated wedges and filters of various "primary" hues, most of the so-called "tint-photometers," spinning disk colorimeters of all types, flicker photometers, etc.

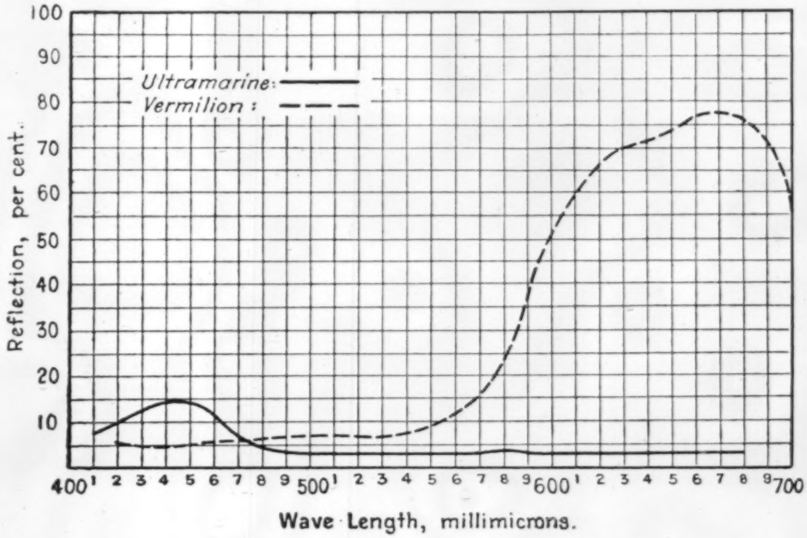

FIG. 1.—Plot of Detailed Analysis Made of Two Pigments by Spectrophotometric Method. These Curves of Spectral Reflection are the Ultimate in Detailed Color Analysis.

3. *Photometric and Color Measurement in Terms of Fundamental Constants of Light Units and the Spectrum.*—The methods of analysis in this class are all dependent upon careful, detailed precision in observation and arrangement. (See Fig. 1.) The instruments themselves are

all finely adjusted, expensive affairs, the highest product of the best mechanicians. They embrace such well-known machines as the spectroscope, the spectrophotometer, the illuminometer, the densitometer, certain special photometers, and all other spectrally-based colorimeters.

4. *Measurement, the Result of Which is Expressed in Terms of Graphically Plotted (Geometric) Arrangements and Relationships.*—This class includes all color diagrams, beginning with Maxwell. In it should be included all developments that exhibit a method of arrangement based upon the three coordinates of space measurement; this class includes, moreover, the revised method proposed in this paper. (In a sense, the spectrophotometers listed in Class 3 are used to make analyses for this type of system, but their resultant graph is expressive of quantity of color rather than of the relative comparison, as related to appearance, of a number of colors. This graph expresses the results of a detailed analysis of any color.)

The instruments used to analyze and classify colors for this type of color arrangement may properly include any type of units which measure, either singly or together, the three accepted qualities of color; but for nearly all such discussions to date, the spinning disk has been relied upon. This sort of instrument is inapplicable in many types of analysis, and the remedy, when this is the case, will be discussed in this paper. The difficulty with an arbitrarily arranged color diagram is that the novice in color technology will inevitably think of its empirically chosen standards as the equivalent of colors with which he is already familiar, and such is not, usually, the case.

Color systems have been largely the creatures of the instruments on which they were evolved and have been limited to the scope of those instruments.

It should be noted that Class 1 above has to do entirely with details of laboratory construction technique, 2 covers apparatus constructed for convenience in process control work; 3 and 4 are the fruitful sources of observation and research.

THEORETICAL PROBLEMS AWAITING SOLUTION.

Regardless of what relation does, or does not, exist between mixture percentage and the visual color relations found through methods of Classes 3 and 4, certain discrepancies between theory and practice must be cleared up before the problem of mixture and color measurement relation can be attacked with hope of complete success.

First, it should be determined what, if any, hue gaps exist in the hue scale formed by the solar spectrum, that is, if it is possible to create hues by any such method as a combination of spinning disks (or other convenient arrangement) that are not in this scale; or whether, on the other hand, certain mixtures of pure spectrum colors will not give the desired result.

Second, a problem closely allied to the above, namely, the determination of the true scale of complementary hues. Sector combinations have been worked out for a large number of these pairs; as yet, however, no satisfactory scale (in terms of wave lengths) is in existence, because of the lack of agreement among all of these scales, expressed in wave lengths.

It is important, from the point of view of convenient application of color to harmony and design work as well as in certain mixture problems, to determine, in terms of both the readings of secondary instruments and in terms of wave lengths, the color mixtures (whether in terms of wave lengths or some other system convertible into these terms) required to match every known hue, and to create its complementary hue.

Some of the most useful "control" instruments do not lend themselves readily to color investigations with fluids, etc.; also the readings of instruments which may be especially adaptable to such practical uses are not always conveniently expressed in terms of fundamental physical constants, hence the necessity of having factors of interchangeability in all these types of instruments worked out on a common basis.

Third, the problem of determining the degree of saturation of a pure color, that is, the degree of admixture with white, required to match a given sample. It is of value, particularly, in the matter of studies for "tinting power" in the sense where this term refers to the power of a coloring material to make appreciable changes in hue, or changes in the "color quality" of a "white" or "black." The point of such investigations should be to determine the intensity of white light, as compared to the intensity of the pure color, that will give the largest number of measurable steps between the original hue and the color obtained by the admixture, ultimately, of the full intensity of this white light.

The fourth and most important problem is to determine the factors of interchangeability between each system or method of color analysis so that colors matched or measured in one system of units can be transposed immediately into the units of measurement of another system.

In particular, while a graphic system of color specification is often convenient, it is, nevertheless, frequently desirable to know the wave length of the dominant hue created by some sector combination, and no method of interchangeability exists for this. A specially designed spectroscope has been constructed, on which it is hoped to carry out this work and work leading to further information about the nature of complementary color pairs.

By this means a system of transposition units will be developed between these two methods as well as the method of matching colors by superposing patches of colored light upon a white surface.

Until such work is done, the absurdity is all too apparent of attempting to seek a relation between the appearance, color, and the arbitrarily designated symbol of a chemical structure.

The recent proposal of G. W. Thompson "to try to develop a monochromatic method of color analysis consistent with the Howland system" is the direction in which laboratory work for industrial application of color has been heading for some time. One of the chief difficulties in accomplishing such a result will probably be in whatever relation is found to exist between the interchangeabilities of "saturation measure," alluded to above, because the relative changes in saturation produced by progressive additions of white light to an unsaturated hue cause a different rate of saturation per unit of this "white" added, than do additions of white in a sector combination where the "white" is a whitened sector. Moreover, Troland has shown[1] that there is an inherent saturation of each of the hues in a normal spectrum which accounts for the relative predominance in appearance of one hue over another. This discovery will undoubtedly affect the consideration of the absolute limits in degree of saturation.

ARRANGEMENT IN COLOR SYSTEMS.

In addition to the vital need that the steps, in the three generally accepted dimensions of color, be computed so as to be in accord with sensitory laws, some other details in the arrangement of measured colors into color lists or systems must be attended to in order to make the display of such groupings effective, as well as to facilitate the selection of any color desired:

1. First of all, attention should be paid to arranging the hue scale. In those arrangements which are based upon the plan that lines of hue are disposed so as to radiate from a central axis, like the spokes of a wheel (Fig. 2), a number of practical difficulties arise with the attempt to lay out or group a large number of colors that differ only slightly in hue. Although the explanation of such systems does not so state,

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[1] American Optical Society Convention, 1921.

the fan-shaped arrangement of a small group of hues, arranged under this scheme, is such as to lead one to believe that colors of high saturation in one hue are further from the colors in an adjacent hue than are colors of low saturation. The practical difficulty arises, moreover, that, no matter how the arrangement is carried out (see Fig. 2), *i. e.*, whether the neutral boundary be considered at A, or A_1, still the space between *r* and *o* may be insufficient to include the desired number of hue steps of a full scale. All too frequently a relatively larger number of steps (samples) will be found to exist at the weakly saturated end of this sector than at the strongly saturated end, and it is an obvious absurdity to build up a scale in which the whole circle A A_1 is the neutral center and then make a series of steps of saturation between *o* and *O* and *r* and *R* when by this plan *oA* (or *rA*) is one color (*e. g.*, neutral gray.) The remedy is so to arrange the "hue chart" that all possible hues are displayed in parallel lines, from the saturated to the unsaturated end (Figs. 3 and 4).

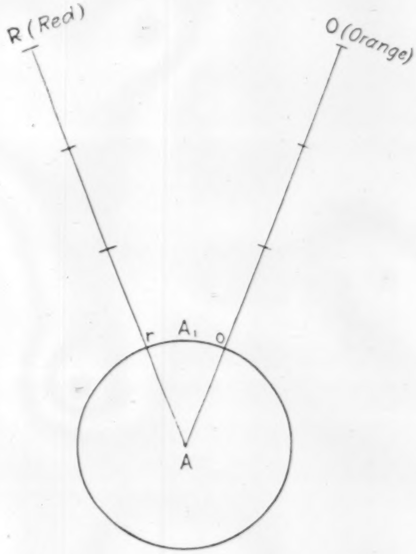

FIG. 2.—Fan-shaped Arrangement of Hues.

2. The second fault in arrangement is to indicate by a few steps the general manner in which a hue scale is to be constructed, and to state, with such a chart, that the intermediate steps can be filled in. Not only is such a procedure unsatisfying, but it leaves room for error in completing the indicated work. The least that can be done is to

indicate, by a reference to wave length of dominant hue, or by other suitable reference, the exact hue of each intermediate line of hues between any two shown. By far the better way is to do this, and then to strive to designate, by sample, or prescribed method, just what each hue step looks like.

3. The third problem of arrangement arises from the practical condition that it is frequently desirable to make up a color grouping of only a very limited range of steps in each color region about which the product groups itself. For instance, often a whole line of manufacture will vary only very slightly in hue, and perhaps a little more or less in the other dimensions. The result is a group of colors that grade off in each dimension but whose total limits of difference in each dimension, if referred to a theoretically complete color scale, are very small indeed.

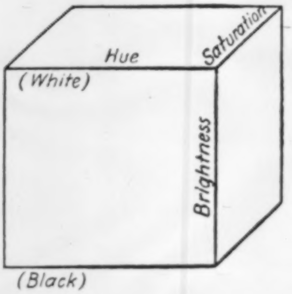

FIG. 3.

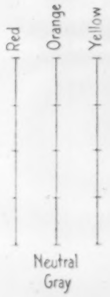

Fig. 4.

The proper system of color grouping should be such that it is readily possible to isolate such a small section of it as the conditions of the application may demand, and that the section so isolated be easily adaptable, in form, to either display or filing purposes (Fig. 4). This property is apparently governed by the outline or shape of the group. According to the spherical form of color arrangement mentioned, a hue chart, limited to a region as described above, would take, roughly, the form of a sector (Fig. 2). This is an inconvenient form for either filing, recording, or reference, especially where many such "regions" must be kept on hand, each separate from the other.

By the parallel arrangement of hue lines, this fault is eliminated, and as all the dimensions are then expressed by variations in the regular three coordinates of space measurement, each at right angles to the other, the grouping is more smoothly compact, and viewing such a "region" enables one to determine, instantly, any extreme and incongruous variations from the "region" type, with a view to eliminating such extreme "numbers" if necessary. (See Figs. 4 and 5.)

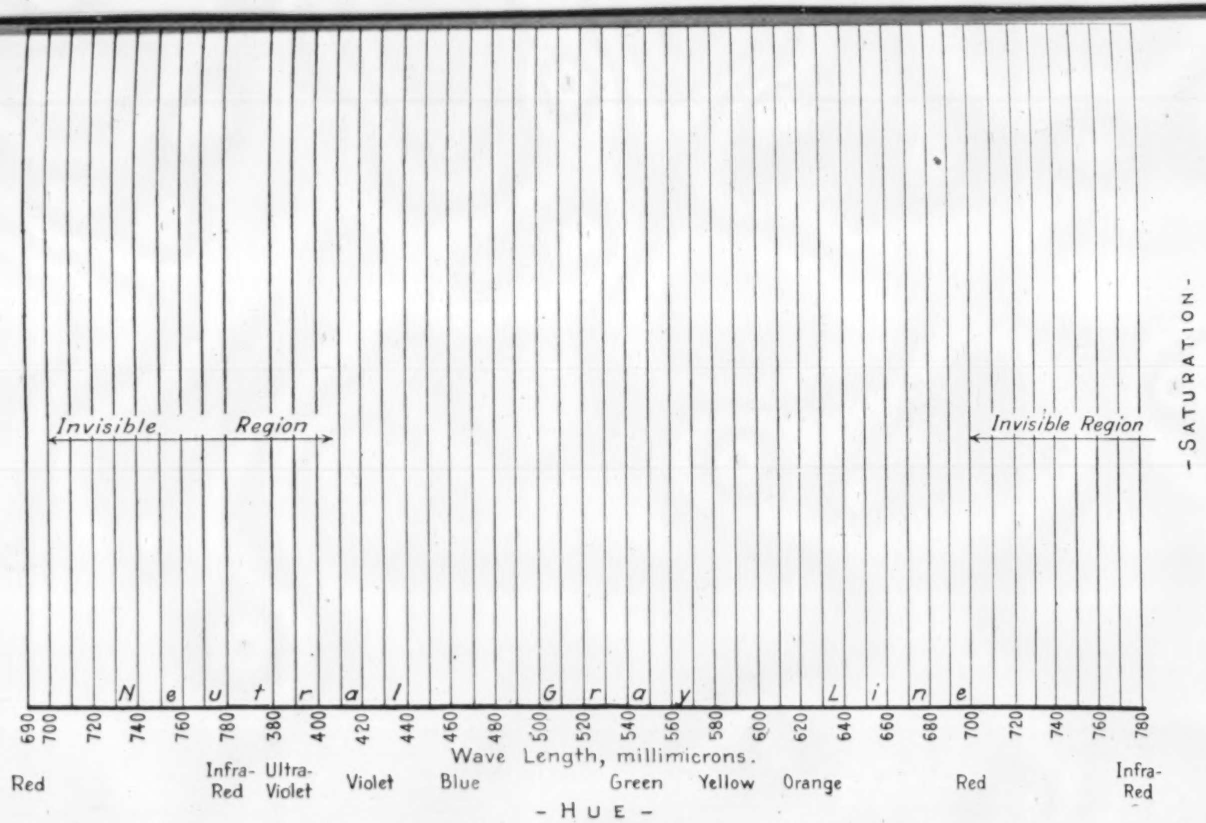
- SATURATION -
Invisible Region
Invisible Region
N e u t r a l G r a y L i n e
690
700
720
740
760
780
380
400
420
440
460
480
500
520
540
560
580
600
620
640
660
680
700
720
740
760
780
Wave Length, millimicrons.
Red
Infra-Red
Ultra-Violet
Violet
Blue
Green
Yellow
Orange
Red
Infra-Red
- HUE -

FIG. 5.—Disposal of Colors on one "Brightness" Plane of the Proposed Arrangement of Colors. Successive "Layers" of this Type Make Up all the Degrees of Brightness Between Black and White.

The hues are laid out in their spectral order; therefore location of a hue is merely location of the line representing its wave-length. (Colors formed by the admixture of two hues will be represented by reference to the two wave-lengths used, etc.)

Degree of saturation is expressed by distance along the hue lines, from neutral gray line to its extremity, and this charter presents one level or degree of brightness. The elements of this method of arrangement combine the elements of the spectral and the graphic methods of expressing color. The revision lies in:

1. Elimination of the radial form of arrangement.
2. Disposal of hue, saturation, and brightness units in terms and ratios expressive of the means by which they are measured.
3. Use of standards which may be demonstrated to view, at will, and the visual connection, therefore, made between the appearance (color) and its graphic representation.

NOMENCLATURE.

In practice, it has been found that relatively small importance attaches to the symbolization applied to those factors of a color measurement that describe (1) the degree of variation from purity, and (2) its position between the extremes of light and dark, provided that the *steps* of such gradation are in accord with those least perceptible differences which a study of the laws of vision dictate.

The unsalable quality in the notation of most color systems expounded up to the present time is that the various sensations corresponding to wave length difference (hue) have been described in terms that not only recall nothing in the experience of the average layman, but these actually do not connote anything whatever in the experience of any but a very limited number of the workers in the field of color itself.

A recent examination of a certain color scale revealed the fact that less than 10 per cent of all the colors named therein were recognizable as even reasonable approximations of the colors of those common objects which they were supposed to resemble. Indeed it was an even smaller percentage that were indubitably identified in this sense of being *representative* of the color of these objects for which they were named.

Let us consider, briefly, the hue scale formed by the colors of the solar spectrum bearing in mind that those colors which are not found in the spectrum may be created by the admixture of two or more of the spectral colors and these mixed with white. It would be impossible, obviously, to designate, offhand, all of these hues by such captions as rose, grass, buttercup, etc., although all these colors named may occur at some step of purity (saturation) of certain of these spectral hues. Such designation would be unwise, because the color buttercup is an uncertain quantity, as a little investigation will convince. Strictly, also, the difference between such an appearance as "buttercup" and "dandelion" involves the further consideration, in addition to hue, of sheen and texture.

It is always possible to arrive at an acceptable color measurement average for such a named hue as "buttercup," that is, the average measurement for a large number of buttercups, and for the present stage of our color evolution, as it applies to commercial standards, this procedure is strongly recommended.

All the known hues should be given not only the wave length reference number or numbers that describe their dominant hue, but as well should be assigned hue names which common experience, and the procedure of color measurement described above, naturally assigns to them. Moreover, such names have immediate application to a very large number of commercial activities, and if it be desired to further restrict these hue names to apply only to a certain class of business it would be easy to develop a scale in which the synonomous names (of each business group it were desired to cover) were listed together.

It is of utmost importance that uncommon and remotely applicable color names be avoided in this plan. In order to make it a success it will be necessary to combine the results of two investigations: the type of measurement-averages described above, and the opinion of a jury of average men and women who shall determine the answer to such questions as whether, "sunflower" or "ox-eyed daisy" is the best terminology for a certain yellow. It is a serious matter—a real foundation of future reference usefulness.

Arbitrarily set numbers as references to certain hues have never been acceptable to any considerable number of color users; they have no inherent logical association with the color fact. Whether or not such names as recommended above be adopted at once for every known hue it is important that every known hue be assigned the equivalent (in either one, or the admixture of two) wave lengths which match it. There will then be a technical basis of reference for each hue, and, as it becomes feasible, the *name list* can be added to, giving finally the association of each hue with colored objects encountered in common experience. Names given to colors that have not the advantage of the "average" selection referred to above applied to them are in danger of being classed as absurd; on the other hand, to leave out the numerical (wave length) classification is to court danger of inaccuracies, and is consequently unwise in a system upon which quality standardization is to be based.

It should, certainly, be as easy for industrial and technical representatives to agree upon a series of well-founded names, which have authentic measurement reference basis, as for them to accept as seasonable *style* a name which is a name only (and may mean anything or nothing at all).

The following parallel lines of effort are recommended for color standardization and for color investigation and research:

INVESTIGATION AND RESEARCH.	STANDARDIZATION.
1. Determination of factors of interchangeability between existing *methods* (not systems) of color measurement. (*Example.*—Sector-combination match in terms of spectrophotometric measurement.)	1. Of the means *of measurement* and the *numerical measure* of each step in each of *three* generally accepted terms of color measurement, just as specifications are written for methods of sampling coal, for instance.

2. Examination of the laws of visual response to assure that the steps of difference (in all three factors of color measure ment) align therewith; examination also of such relations as exist between pairs, etc., of colors, such as complementary pairs and similar relations, to establish the *laws governing and actual measurement of same.*	2. Of most useful methods of arrangement of color scales.
3. Construction of color (hue) scales which shall include all the known hues, assigning not only the equivalent references of measurement of these in terms of wave lengths of light but also *names* derived by the determination of what colored objects in common experience have as *average hue* the particular hue existant in this scale at this point. (This is done to associate the *characteristic* hue, of common association with such objects, with the hue in the theoretically built-up scale.)	3. By co-operation with other professional societies and by acceptance of the constants of fundamental reference in color measurements: (*a*) White (*b*) Black (*c*) Least perceptible differences (steps) in each of the three factors of color measurement.
	4. Of the "average measurement" of colors of common objects as a basis *for names* of hues in the hue scale adopted.

In view of the foregoing needs that have been encountered in industrial applications of color, attention to the results of the efforts of workers in the realm of pure science, logic, and psychology, as applied to this problem, are recommended as fundamental.

Acknowledgments.—The foregoing conclusions are based upon an extensive investigation of the application of arrangements and systems of color measurement to industrial use and results experienced with them in practise.

Mr. G. W. Thompson suggested the advisability of publishing the results of this work, at this time, to assist in furthering the progress of the art.

Thanks are due Mr. Ingalls for practical advice in the matter investigated, and for supplying us with considerable material for our work.

We wish to acknowledge also the loan by Mr. Norman Macbeth of apparatus for the production of daylight illumination.

AN APPLICATION OF THE PFUND COLORIMETER TO THE DETERMINATION OF TINTING STRENGTH OF WHITE PIGMENTS.

J. H. Calbeck[1] and C. P. Olander.[2]

Introduction.

We frequently have occasion in this laboratory to compare many different samples of the same kind of pigment for color strength. Since many of the samples examined differ greatly in initial brightness, and since we desired to make the determination as accurate as possible as a control on the quality of the pigment, we found it necessary to work out a method whereby this initial difference in brightness had no effect and whereby the comparison obtained could be assigned numerical values.

The determination of color strength necessitates the mixing of pigments. The pigments of all colors, except white, are usually mixed with a white pigment. The richness in white of the resulting mixture and the color strength of the pigment are inversely related. A white pigment must be tested with a colored one, the diluent ordinarily being lampblack, the richness in white being a direct indication of the strength of the white pigment. The tinting strength of a white pigment may therefore be defined as the power of a given quantity of pigment to resist change in brightness when mixed with a definite amount of standard black.

The use of the terms pigment and diluent as herein employed are defined as follows:

> Pigment is that component of the mixture undergoing strength measurement, *e. g.*, the white pigment. Diluent is the auxiliary, *e. g.*, the standard lampblack.

The brightness of the bluish gray color obtained when a mixture of a white pigment, a black, and a colorless vehicle are ground up together depends upon the nature of the three substances and their relative amounts. In making a strength determination, great care must be taken to use always the same volume of vehicle and the same weight of lampblack and pigment, then the resulting gray will depend upon the color strength of the white pigment only. The variation in color strength of different pigments is dependent upon refractive index (of pigment and vehicle), fineness and initial brightness. This difference in initial brightness is usually neglected.

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[1] Director of Research, Eagle-Picher Lead Co.

[2] Formerly Research Chemist, Eagle-Picher Lead Co.

Perhaps a strength comparison should be based upon equal volumes rather than equal weights, but we have found it more convenient to make calculations upon a weight basis.

TYPICAL WELL-KNOWN METHODS.

Of all the methods employed in the determination of color strength, the following taken from *Bulletin No. 88*, U. S. Bureau of Standards, seems to be the general procedure:

> "Weigh accurately 0.01 g. of lampblack, place on a large glass plate or stone slab, add 0.2 cc. of linseed oil, and rub up with a flat-bottomed glass pestle or muller; then add exactly 10 g. of the sample and 2.5 cc. of linseed oil, and grind with a circular motion of the muller 50 times; gather up with a sharp-edged spatula and grind out twice more in a like manner, giving the pestle a uniform pressure. Treat another 0.01 g. of the same lampblack in the same manner, except that 10 g. of standard leaded zinc oxide is used instead of the 10 g. of the sample. Spread the two pastes side by side on a glass microscope slide and compare the colors. If the sample is as light as, or lighter in color than the 'standard,' it passes this test."

When numerical values are desired, small batches of standard are ground up with different weights of lampblack and the color strength of the unknown determined by matching with the different batches. For example, if a given weight of sample shows the same brightness when ground with 10 mg. of lampblack that the same quantity of standard does when ground with 9 mg., then the sample would be graded 10 per cent weak. Methods similar to this have been used very extensively but no attempts have been made toward standardization, and each operator compares his own standard by his own chosen method.

Other laboratories having photometers or colorimeters have devised methods for making these tests but so far as we have been able to learn, nothing of this kind has ever been published.

NEW METHOD.

This investigation was undertaken to perfect a method for determining color strength involving only a minimum personal error, taking into account differences in brightness in various pigments and amenable to exact mathematical evaluation.

The method consists in determining the ratios by weight of the sample to lampblack and standard to lampblack which will produce equal changes in brightness within the same range. The strength of the sample compared to the standard is easily calculated from this data.

The Pfund colorimeter (*Proceedings*, Am. Soc. Test. Mats., Vol. XX, Part II, p. 441 (1920)) was used for the brightness determinations. Any colorimeter or photometer adapted to use with white pigments should work equally well. The instrument was calibrated with samples submitted by Dr. Pfund. Colorless glycerin was used as a grinding vehicle and the black finally adopted for the work was a very weak but fine mineral black, a large quantity of which we had on hand. The green color filter was used in all cases.

Standard Strength Curves.—It is first necessary to prepare a standard strength curve. For very accurate work, it is necessary to prepare a curve for each kind of pigment to be tested. Fig. 1 shows a strength curve for lithopone and Fig. 2 shows one for zinc oxide. The curves for zinc oxide show results obtained when a blue, green and red color filter is used in the colorimeter. However, only the values obtained with the green filter are used, although interesting variations in strength relations may be obtained by using the other filters, especially when the samples examined show difference in initial color values.

The original brightness of the standard pigment was first determined. The value for each of a series of mixtures consisting of 10 g. of pigment to increasing amounts of diluent was then determined. The curves show the change in brightness with change in black content. Each kind of pigment requires a different amount of vehicle to make a paste of proper consistency for the colorimeter. The amount of vehicle must be accurately measured out for each determination. We found that the best results are obtained when the following amounts of glycerin are used with 10 g. of pigment:

White lead	4 cc.
Lithopone	6 cc.
Zinc oxide	9 cc.

Determination of Color Strength.—To determine the color strength of an unknown pigment, its original brightness and its brightness when mixed with a known weight of standard black are the only experimental values necessary. The standard curve supplies the additional data required. An example will make clear the simple calculation:

Ten grams of lithopone and 6 cc. of glycerin were rubbed up and an initial brightness of 91.6 obtained. Then 10 g. of lithopone, 6 cc. of glycerin and 2 mg. of standard black were examined in the colorimeter and a brightness of 72.5 obtained.

Now, from the standard strength curve, the amount of diluent necessary to change the brightness of the standard lithopone from 91.6 to 72.5 is found as follows:

To change from 93 per cent, the initial brightness of the standard, to 72.5 per cent requires 1.95 mg. of lampblack.

To change from 93 per cent to 91.6 per cent requires 0.04 mg. of lampblack, a difference of 1.91 mg. of lampblack.

The difference, or 1.91 mg., is that amount of lampblack which added to 10 g. of standard lithopone of equal brightness will produce the same change in brightness as 2 mg. of standard black added to 10 g. of the sample.

Therefore $\frac{2}{1.91}$, or 1.05, is the strength of the above sample of lithopone. Therefore, 10.5 g. of the standard would be required to give the same brightness when mixed with 2 mg. of standard black as 10 g. of the sample, if the standard were the same brightness as the sample. In other words, we get a result similar to what we would obtain had we darkened the standard to match the sample before we made the color strength determination.

If differences in initial brightness are not to be considered, then the ratio $\frac{2}{1.95}$ or 1.035 represents the strength of the sample, a very small difference when the initial brightnesses are so nearly alike. The following tables show results on a number of samples of zinc oxide and lithopone.

TABLE I.—SHOWING HOW THE INITIAL BRIGHTNESS MAY EFFECT DIFFERENCE IN STRENGTH READINGS.

2 mg. of standard black and 10.0 g. of lithopone.

	BRIGHTNESS.		STRENGTH.		
PAINT NO.	INITIAL.	FINAL.	UNCORRECTED.	CORRECTED.	DIFFERENCE.
1 (Standard)	93.0	72.2	100	100	0.0
2	91.8	71.3	91.0	92.0	1.0
3	89.6	72.8	106	113	7
4	89.1	70.8	86	92	6
5	86.8	70.3	82	92	10
7	86.0	71.6	93.5	111	17.5
8	84.4	70.5	83.0	102	19

TABLE II.—STRENGTH OF SEVERAL ZINC OXIDES.

3.2 mg. of standard black and 10 g. of zinc oxide.

	BRIGHTNESS.		STRENGTH.		
PAINT NO.	INITIAL.	FINAL.	UNCORRECTED.	CORRECTED.	DIFFERENCE.
1 (Standard)	93.0	65.0	100	100	0.0
2	82.3	61.7	85	102	16.0
3	82.2	54.1	62	71	9.0
4	82.0	61.2	83	100	17.0
5	80.8	55.1	65	76	11.0

The figures given in Table I were chosen from a great number of determinations made on lithopone. It will be observed that when the difference between the standard and the sample is small, the difference in strength is small, smaller in fact than could be readily distinguished with the unaided eye if the two mixtures were compared side by side on a slide in the usual manner. But this difference increases rapidly as the sample drops in brightness.

Table II, in which zinc oxide is used, shows the effect of choosing as a standard an oxide with a higher brightness.

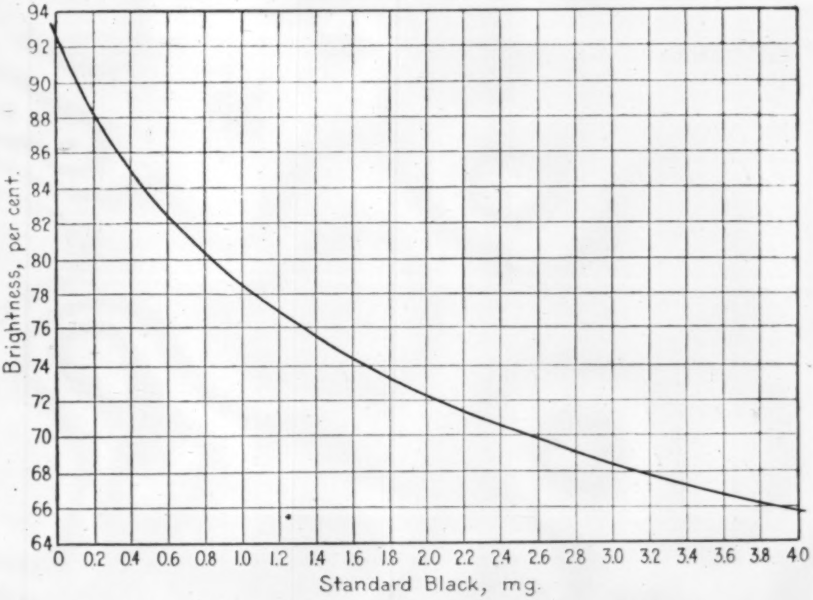

FIG. 1.—Additions of Standard Black to 10-g. Portions of Standard Lithopone.

Precautions.—The sources of error are involved in mixing, coating the disks of the colorimeter and reading the instrument. The reducing effect of grinding was made uniform by using the same amount of glycerin in each mixture and giving each mixture the same number of turns with the muller. The thickness of the paint film spread on the instrument disks were made as constant as possible, experience proving that the brightness results become lower as the thickness increases. A perfection of the colorimeter conducive to a high degree of sensitivity determines mainly the accuracy to which this method is capable.

DISCUSSION.

This method makes possible the comparison in strength of a sample of any brightness to a standard of the same brightness. The determination on this basis is very essential. A neglect of this difference gives erroneous results. Suppose two samples have the same strength but different brightnesses. To reduce them to a lower and identical brightness would naturally require different amounts of lampblack, the sample of higher brightness requiring more. It would therefore appear stronger. The existing practices therefore result in slightly higher values if the sample is brighter than the standard, lower if darker than the standard. The consideration of brightness differentiates this method from existing practices.

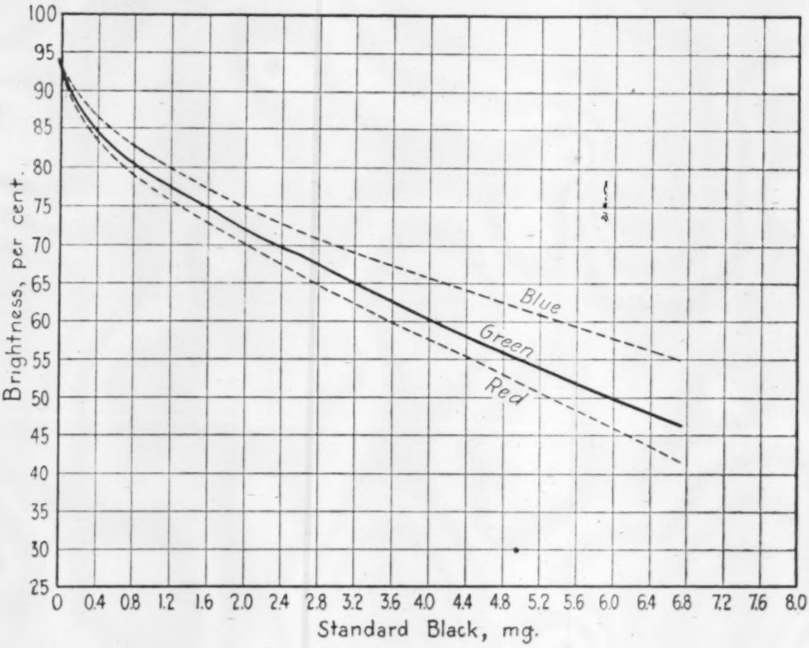

FIG. 2.—Additions of Standard Black to 10-g. Portions of Standard Zinc Oxide.

A practical determination of strength should not involve a brightness correction. The paint manufacturer wants to know the strength of the sample as compared to a standard of a fixed brightness, not to a standard of the same brightness as the sample. The brightness therefore becomes a factor of strength. When the brightness correction is neglected, the procedure is facilitated. A brightness observation of a mixture of a known ratio of sample and lampblack is the only experimental result needed. A reading from the curve gives the amount of standard black required to bring the standard to the brightness of the mixture. This value compared with the amount of black used gives the color strength as already explained. No additional data is necessary for the strength calculations.

A medium brightness standard for practical work would be as suitable for preparing the curve, as a high brightness standard. A correction for brightness could not be obtained if the brightness of the sample exceeded that of the standard. The selection of a high brightness standard was therefore necessary.

An examination of the standard strength curve shows that the sensitivity, the rate of change of brightness with increase in black content, is very great at first, but rapidly diminishes. This behavior indicates that there probably is a certain change conducive to the greatest accuracy in strength determination. There are objections to the use of either too little or too large amounts of black. The former procedure gives great sensitivity but involves a high percentage of error. A brightness consideration is extremely important in this case. This regard, to be sure, is unnecessary in the latter case, for the fraction of the largest quantity of black required to effect the change in brightness between the standard and sample is negligibly small. The sensitivity, however, is large and the error consequently great. A larger change in brightness, than involved in the determination as conducted, may prove more desirable.

This method could well form the basis of a standard process for determining strength. An agreement as to a source of supply of standard pigment and diluent and a standard method for procedure for the determination of brightness would be necessary.

DISCUSSION.

The Chairman.

THE CHAIRMAN (MR. G. W. THOMPSON).—I should like to ask Mr. Calbeck whether he practically can get the same readings on repeat determinations, or how close he can get readings on repeat determinations on the same samples.

Mr. Calbeck.

MR. J. H. CALBECK.—That depends entirely on the accuracy of the colorimeter. Our colorimeter shows a possible error sometimes as great as 3 per cent, and when it is not working properly and not properly adjusted, it sometimes shows a 5-per-cent error on brightness, but we usually avoid that by checking the colorimeter against a standard and by making a correction we can get the error within 1 per cent. For example, a pigment showing a color strength of 92 per cent should be within one or two per cent of the correct value. If we were comparing a sample of 92 per cent with one that was 93 per cent, the chances are that this small difference is less than the probable error.

The Chairman.

THE CHAIRMAN.—That's remarkably close. We have never felt that it would be safe—considering the operation of rubbing up which may affect the results that you get, and considering also the difficulty of observation where you are taking the light through an apparatus and through optical parts of the apparatus—to report results closer than 5 per cent, so we figure our standard at 100 and report 95, 90, 85, 105, 110 and so on, and for practical purposes it has answered very well.

Mr. Calbeck.

MR. CALBECK.—I should like to emphasize the fact that mineral black is an exceptionally good material to use in any tinting strength determination, because, being extremely coarse pigment when compared with lampblack and other blacks, it is not flocculated. The mineral black I used was quite black. It was not one of those slaty colored mineral blacks you often see. It was good and black, but at the same time it was just fine enough so as not to be gritty when ground up. My definition of black is neutral color of extremely low brightness. The blacks that we used were not perfect blacks. That is, considerable light was reflected by them, much more than would be reflected by carbon black or by lampblack. We are not measuring a color difference here at all. It is just a pure matter of measuring diffused reflection, first, of pigment alone and then of the pigment after it is darkened with black.

HIDING POWER OF WHITE PIGMENTS.[1]

BY R. L. HALLETT.[2]

Many statements have been made in regard to the hiding power of pigments, and the object of this paper is to discuss some of the fundamental conceptions of hiding power and to bring out more clearly the relative hiding power of the various white pigments. By hiding power of a pigment is meant its ability, when used in paint, to conceal a surface over which it is applied.

Strictly speaking, this paper probably refers to the opacity of the white pigments rather than to their hiding power, as the American Society for Testing Materials' definitions for these terms, given under the Standard Definitions of Terms Relating to Paint Specifications (D 16 - 15),[3] are as follows:

> "*Opacity.*—The degree of obstruction to the transmission of visible light."
>
> "*Hiding Power.*—The power of a paint or paint material as used to obscure a surface painted with it."

Standard test conditions were used in the tests described in this paper, and it is, therefore, evident that many of the reported results refer to opacity rather than to hiding power, as hiding power is a practical term and always carries with it the idea of a practical paint mixture applied at a practical spreading rate. The oil-taking power of a pigment, which determines the paint composition and the practical spreading rate of the paint, as well as the opacity of the pigment itself, must be considered in estimating hiding power. A pigment which has low oil-taking power may produce a paint with greater hiding power than a paint made with another pigment which has greater opacity but also greater oil-taking power. Nevertheless, because of the more popular understanding of the term "hiding power," it was decided to use it in this paper.

It was thought best to limit the scope of this paper to the white pigments so as not to complicate the problems involved. The white pigments considered are carbonate white lead, basic lead sulfate, titanox, zinc oxide, and lithopone. No other white pigments were used in this work, because the other so-called white pigments, such as asbestine, whiting, china clay, silica and gypsum, when mixed with the ordinary paint vehicles, lose nearly all of their opacity or hiding power.

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[1] Contributed by the Research Laboratories of the National Lead Co.

[2] Chemist, National Lead Co., Brooklyn N. Y.

[3] 1921 Book of A.S.T.M. Standards, p. 696.

In the work on the hiding power of the white pigments, several methods of test and a number of different instruments were used, particularly the cryptometer, described by Dr. A. H. Pfund,[1] and the hidimeter or hiding power instrument, described by the author.[2]

HIDING POWER AND THICKNESS.

The first problem considered was the determination of the law by which the hiding power of a paint film varies with its thickness. From the theoretical considerations, it was assumed that hiding power is a geometric function of the thickness, which might be illustrated by saying that if a certain thickness of paint film shows a 50 per cent hiding of a surface over which it is applied, twice the thickness of paint film will show 75 per cent hiding; three times the thickness will show 87.5 per cent hiding, and so on, complete hiding being theoretically obtained only by a paint film of infinite thickness. This supposition may be expressed mathematically, as follows:

The general equation would be

$$S = a + ar + ar^2 + ar^3 \ldots\ldots\ldots ar^{n-1}$$

where

S = hiding of any thickness of a paint film, expressed as a fraction of unity = sum of hiding of all terms or units of thickness;
n = Number of terms = number of units of thickness;
a = first term = hiding of first unit of thickness;
l = last term = hiding of last unit of thickness;
r = common ratio;

from which

$$S = \frac{rl - a}{r - 1}$$

$$l = ar^{n-1}$$

in this case

$$r = 1 - a$$

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[1] *Journal* of the Franklin Institute, November, 1919.

[2] *Proceedings*, Am. Soc. Test. Mats., Vol. XX, Part II, p. 426 (1920).

and therefore

$$t = a(1-a)^{n-1}$$

$$S = \frac{(1-a)\, a\, (1-a)^{n-1} - a}{1 - a - 1}$$

$$S = \frac{a(1-a)^{n} - a}{-a}$$

$$S = 1 - (1-a)^{n}$$

$$(1-a)^{n} = 1 - S$$

$$1-a = \sqrt[n]{1 - S}$$

$$a = 1 - \sqrt[n]{1 - S}$$

To demonstrate the truth of this theory, a number of paints were prepared, each paint being made on the same volume formula. A different white pigment was used in each paint, and linseed oil was used for the vehicle. These paints were spread over panels previously painted white with a broad black stripe. The same spreading rate was used for each paint, so that the same volume of pigment was applied on unit area on each panel. The thickness of each paint, required to give apparent complete hiding, was measured with the cryptometer, and the percentage of hiding of the black stripe on each panel was measured with the hidimeter referred to.

König and Brodhun[1] have shown that "the least difference in brightness, which is perceptible to the eye, is from one to two per cent," and, in making the calculations, it was, therefore, considered that the cryptometer readings, which indicated thickness for complete hiding, really indicated thickness for 98 per cent hiding, as, according to the theory, complete hiding would only be obtained by an infinite thickness of paint film. Using the formulas developed, the cryptometer readings for 98 per cent hiding were used in calculations to show, for each paint, the percentage of hiding corresponding to the thickness of film used on the black-striped panels, which thickness was determined from the spreading rate. The percentage of hiding for each kind of paint used in these tests, both as actually determined by the hidimeter in the panel tests and as calculated for the same paint thickness from the cryptometer readings, in accordance with the geometric formula, is shown in the following table:

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[1] P. G. Nutting, "Outlines of Applied Optics," p. 126 (1912).

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from which

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$$l = ar^{n-1}$$

in this case

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[1] *Journal* of the Franklin Institute, November, 1919.

[2] *Proceedings*, Am. Soc. Test. Mats., Vol. XX, Part II, p. 426 (1920).

and therefore

$$i = a(1-a)^{n-1}$$

$$S = \frac{(1-a)\,a\,(1-a)^{n-1} - a}{1 - a - 1}$$

$$S = \frac{a(1-a)^{n} - a}{-a}$$

$$S = 1 - (1-a)^{n}$$

$$(1-a)^{n} = 1 - S$$

$$1-a = \sqrt[n]{1 - S}$$

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To demonstrate the truth of this theory, a number of paints were prepared, each paint being made on the same volume formula. A different white pigment was used in each paint, and linseed oil was used for the vehicle. These paints were spread over panels previously painted white with a broad black stripe. The same spreading rate was used for each paint, so that the same volume of pigment was applied on unit area on each panel. The thickness of each paint, required to give apparent complete hiding, was measured with the cryptometer, and the percentage of hiding of the black stripe on each panel was measured with the hidimeter referred to.

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[1] P. G. Nutting, "Outlines of Applied Optics," p. 126 (1912).

KIND OF PAINT.	ACTUAL HIDING READINGS ON PAINTED PANELS.	HIDING FOR SAME PAINT THICKNESS CALCULATED FROM CRYPTOMETER READINGS.
Carbonate White Lead	77 per cent	77 per cent
Basic Lead Sulfate	57 "	57 "
Titanox	92 "	93 "
Zinc Oxide	74 "	74 "
Lithopone	62 "	63 "

These two sets of figures are so nearly alike that they appear to be a reasonable demonstration that the hiding power of a paint film is a geometric function of its thickness.

The same law was demonstrated in another way, and additional evidence was obtained to show that hiding power is a geometric function of the thickness of a paint film. A paint of practical brushing consistency was made with carbonate white lead for the pigment and linseed oil, with the necessary amount of dryer, for the vehicle. This paint was applied to five panels which had been previously painted white with a black stripe. The panels were all exactly the same size, and the paint was so applied that the panels received, respectively, 2, 4, 6, 8 and 10 g. of paint. In other words, the thickness of paint film and the amount of pigment varied at a constant rate.

After the paint on the five panels was dry, the hiding of the paint on each panel was measured with the hidimeter, and the following results were obtained:

PANEL No.	RELATIVE THICKNESS OF PAINT FILM.	HIDING.	INCREASE IN HIDING.	INCREASE IN HIDING EXPRESSED AS PERCENTAGE OF INCREASE NECESSARY TO GIVE TOTAL HIDING.
1	1	18 per cent	18 per cent	18.0 per cent
2	2	33 "	15 "	18.3 "
3	3	45 "	12 "	17.9 "
4	4	56 "	11 "	20.0 "
5	5	65 "	9 "	20.4 "

The figures given in the last column are not all exactly the same, but they are so nearly alike that they seem to indicate that, as the thickness of paint increased, the hiding power also increased, but in geometric proportion to the thickness.

TINTING POWER AND HIDING POWER.

An investigation was made to determine the relation between the tinting power and hiding power of the white pigments. A number of samples of each of the five white pigments were used in these tests. The pigments were made into paints by mixing them with bleached linseed oil. A single pigment was used in each paint, and the paints were all made on the same volume formula; that is, they all contained the same volume of pigment, and the same volume of vehicle. The hiding power of the white pigments was measured by testing the paints in the cryptometer.

Using the same volume formula, the same pigments were made into paints with linseed oil and dryer. These paints were spread on black-lined panels, using the same spreading rate for each paint, so that each panel had the same volume of pigment on a unit surface. The hiding power of the pigments was then determined by measuring the hiding of each panel with the hidimeter.

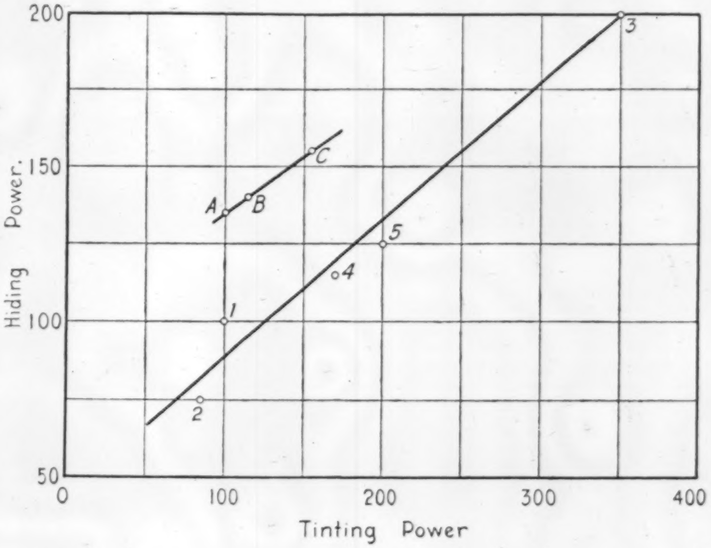

FIG. 1.—Hiding Power and Tinting Power of White Pigments, Weight Basis.

The hiding power results obtained with the cryptometer and hidimeter were then tested in a third way by applying the same paints to black-lined panels, using the proper spreading rates to give equal hiding on all of the panels, as indicated by the cryptometer and hidimeter hiding power figures. The panels were then compared to see if the hiding power figures were confirmed by the panel tests. It was found that the cryptometer and hidimeter results were slightly erratic, but the final results, as corrected by the practical panel tests, are probably fairly accurate.

The pigments were tested for tinting power by comparing them with carbonate white lead, the tinting power of which was taken as the standard and was designated 100. The tinting power determinations were made by adding a standard amount of lampblack to the sample being tested, and then adding different amounts of lampblack to the standard carbonate white lead sample until the gray color so produced just matched the gray color of the sample under test. The amount of lampblack required for the standard white lead sample compared to the amount added to the sample being tested determined the tinting power. The comparisons were made with the samples mixed with bleached linseed oil. The hiding power and tinting power figures varied somewhat with different samples of the same kind of pigment, but average results, showing hiding power and tinting power of representative average samples of the various white pigments, are shown in the following table:

No.	Pigment.	Hiding Power, sq. cm. per g.	Relative Hiding Power, Weight Basis.	Relative Hiding Power, Volume Basis.	Tinting Power, Weight Basis.
1	Carbonate White Lead........	40	100	100	100
2	Basic Lead Sulfate............	30	75	72	85
3	Titanox......................	80	200	128	350
4	Zinc Oxide....................	46	115	96	170
5	Lithopone....................	50	125	80	200

The tinting power and hiding power values on a weight basis were plotted on squared paper, using the tinting power values for one coordinate and the hiding power values for the other. The curve obtained is shown in Fig. 1.

The pigments used for this curve are the ones given in the table, and are numbered one to five on the curve. These plotted points so nearly assume a straight line that it seems very probable that tinting power is a direct measure of hiding power under certain conditions.

A slightly tinted carbonate white lead sample with a strong gray tone was tested for tinting power and hiding power, and was then plotted on the same paper. Its position is shown at *A*. The same tinted sample of carbonate white lead was then pulverized very finely in an agate mortar, and was again tested for hiding power and tinting power. When the pulverized sample was plotted it occupied the position *B*, forming with *A* a straight line approximately parallel to the line made by the other pigments, which shows that the increased fineness increased the hiding power and also the tinting power, but did not change their relation to each other.

The sample of zinc oxide used in the original tests, Sample No. 4, was then tinted with a trace of black until its color approximately matched that of the gray tone carbonate white lead sample. It was then tested for tinting power and hiding power, and, when plotted, was found to occupy the position *C*. *A*, *B* and *C* fall approximately on a straight line parallel to the line formed by the white pigments. This investigation seems to show that, with white pigiments which have exactly the same color, the hiding and tinting powers are direct measures of each other, and that the addition of other colors tends to decrease the tinting power and increase the hiding power.

A large part of the experimental work on which this paper is based was done by M. R. Paul and O. W. Larson of the Research Laboratories of the National Lead Co.

DISCUSSION.

Mr. Calbeck.

MR. J. H. CALBECK.—This is a very interesting paper, indeed, and bears out in many ways experiments that we have conducted. The two points that I have to suggest I believe are in direct line with the ideas presented by Mr. Hallett. Two years ago when Mr. Pfund described to us his colorimeter, he made a statement to the effect that hiding power determinations made with a cryptometer were affected by the initial brightness, and he at that time suggested that for every 1 per cent decrease in brightness a pigment increased in hiding power 4 per cent. He also published cryptometer values, one for sublimed white lead, for which he gave a figure of 172 sq. ft. per gallon, and the other for basic carbonate white lead for which he gave a hiding power of 243 sq. ft. per gallon. We immediately began some experiments, and made this interesting discovery: The basic sulfate white lead that we used, and we made a great many determinations with both sublimed white lead and basic carbonate, was invariably brighter than the basic carbonate white lead, but when we added lampblack together with some sponge lead in order to get exactly the same tone that the carbonate under consideration had, we increased, by cryptometer readings, the hiding power of the sublimed white lead to exactly 242 sq. ft. per gallon. Now, the paper that I have just presented[1] shows the effect of differences in brightness on tinting strength. We attempted to discover some sort of an arrangement, some sort of relationship, such as is shown in Fig. 1 of Mr. Hallett's paper, but we failed. We corrected, both for brightness in our hiding power determinations, as determined by the cryptometer, and for difference in brightness on the tinting strength determinations, but we failed to get any relationship. Nevertheless, I believe that a relationship similar to the one shown there exists, and I think that the reason we failed was because there was another factor that varied in our experiments. We took for our work a number of pigments, all chemically the same but made by different processes. We made a microscopic examination, a very accurate microscopic examination, and took photomicrographs and also made counts of the particles according to the method of Green. This method is described in the *Journal* of the Franklin Institute for November, 1921. We discovered a marked

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[1] J. H. Calbeck and C. P. Olander, "An Application of the Pfund Colorimeter to the Determination of Tinting Strength of White Pigments." See p. 515.—ED.

Mr. Calbeck difference in both the particle size and the shape of the pigments under consideration, and we decided that this was the reason that we failed to get any relationship between hiding power and tinting strength. Mr. Hallett's experiments evidently had been made with pigments very nearly alike as to particle size and shape, and when he corrects for differences in brightness, that is, brings them all to the same tone of gray, he should get a very good relationship, and I think that is just the feature we were looking for but failed to find. However, I do believe that it is necessary, both in hiding power determinations and in tinting strength determinations where a comparison between the true quality of pigments is concerned, that the difference in initial brightness must be given due consideration.

Mr. Busby. MR. H. S. BUSBY.—While the readings may have been within the instrumental error, it is likely that an improvement might be made upon the apparatus to the extent that accuracy of measurements might be made to depend upon some adjustment of reflected light values instead of just contact of surfaces.

In this way the condition might be measured with greater refinement than if it were subject, to any considerable degree, to those instrumental errors which arise from mechanical imperfections.

Mr. Hallett. MR. R. L. HALLETT.—In regard to Mr. Calbeck's remarks, I would like to say that the pigments which were used in these tests varied greatly in particle size and in composition. One of the pigments was carbonate white lead, one was basic lead sulfate, one was zinc oxide, one lithopone and one Titanox, varying greatly in composition, physical structure and size of particle, and what we tried to work out, and believe we did work out, was that the physical characteristics which change the hiding power also change the tinting power, and that, even under these widely varying conditions, the hiding power and tinting power are direct measures of each other.

While I do not wish to say that if these pigments had 100 per cent brightness or luminosity, the tinting power - hiding power line would show zero hiding power, corresponding to zero tinting power, I wish to indicate the possibility that such may be the case, because all of our work points to the fact that as we increase the brightness or luminosity, the line certainly approaches zero hiding power for zero tinting power, and there is a possibility that with 100 per cent luminosity it may pass through zero hiding power.

THE PROBLEM OF DURABILITY TESTS FOR TRANSFORMER OILS

By T. G. Delbridge.[1]

The rapid growth of electric current transmission involves the use of an increasingly large volume of the liquid insulating material commonly known as transformer oil. The importance of such a product in the economic life of to-day and to-morrow is self-evident. The estimated consumption of transformer oil in the United States for the year 1921 was fifteen million gallons having a market value of over two million dollars. Quantity, however, has not been the sole demand of the electrical industry. High quality is essential because the use of poor transformer oil is not only expensive but involves an unjustifiable hazard to life and property.

Transformer oil as used in this country at the present time is a hydrocarbon mixture derived entirely from petroleum, a fact which adds emphasis to the value of this great national resource and to the need for its conservation. The function of a transformer oil is to dissipate the heat generated in the transformer and at the same time provide adequate electrical insulation between surfaces of wide difference in potential. The *initial* requirements for a good transformer oil are three-fold: first, high electrical insulating quality as indicated by dielectric strength and resistivity; second, ability to dissipate heat as indicated by viscosity, specific heat, heat conductivity, cold test, etc.; and third, suitability from the standpoints of evaporation loss and of safety from fire hazard as indicated by the flash point. Fully as important as these three initial requirements is that of durability or the ability of the transformer oil to retain its essential original properties even after prolonged use. Good transformer oil must be suitable at the start, must continue to be suitable and the finish, if there be one, must not be the fault of the oil.

Transformer oils in service may deteriorate as to electrical insulating efficiency through chemical formation of water, of organic acids or soaps derived from the action of such acids on metallic components of the transformer, and possibly on account of suspended solid decomposition products. In the case of hydrocarbon oils, deterioration of this sort can occur only in the presence of oxygen, which for practical purposes means air. Obviously then, it is desirable whenever possible to protect transformer oil from exposure to air. While some transformers are designed to accomplish this purpose, yet countless transformers are now in satisfactory use where such a change would involve inconvenience and financial loss. Hence it is necessary to provide oils that will pass a durability test to cover decrease in insulating value due to oxidation.

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[1] Chief Chemist, The Atlantic Refining Co., Philadelphia.

The deterioration of transformer oils as regards heat dissipation is somewhat more complicated. The oil must absorb the heat generated in the core and windings of the transformer, circulate to a cool or cooled surface and there transfer the heat. The oil during use may become less effective in this respect through one or both of two causes; first, retarded circulation, and second, decreased rate of heat transfer between oil and the confining surfaces. Circulation will be hindered if the viscosity of the oil is increased by evaporation or by chemical changes. Whether or not the products of such chemical change are soluble in the oil is immaterial since suspended matter will make the mixture more sluggish. The second cause of deterioration as regards heat dissipation is the coating of confining surfaces by solid matter formed either directly from the oil itself or indirectly by the action of acid decomposition products on metal. In either case, the product is a sludge and being a poor conductor of heat is seriously objectionable. Satisfactory cooling can be accomplished only when heat transfer takes place into a freely circulating liquid medium and at surfaces kept substantially clean.

The chemical changes in transformer oils during use appear to be due chiefly to oxidation, accelerated by catalysts present, such as metals, metallic compounds, resins and even atmospheric dust. While some chemical change may occur in the absence of oxygen, this would seem to be of minor importance. The susceptibility of transformer oils to oxidation under service conditions may be lessened and controlled by judicious refining of the oil but is not likely to be eliminated. Hence from this point of view, durability tests based on oxidation will have continued usefulness. The following shows the relations described.

EFFECT.	DIRECT CAUSE.	INDIRECT CAUSE.
I. Decrease in insulating value.—		
	1. Water	Oxidation.
	2. Organic acids	Oxidation.
	3. Soaps	Oxidation and combination with metal.
	4. Suspended solids (?)	Oxidation and other chemical action.

EFFECT.	DIRECT CAUSE.	INDIRECT CAUSE.
II. Decrease in heat dissipating value.—		
	1. Retarded circulation due to:	
	(*a*) Increased viscosity	Oxidation yielding thickened oil or mixture of such oil and suspended matter. Evaporation of less viscous components.
	(*b*) Obstruction to flow by solid matter (sludge)	Oxidation and other chemical action.
	2. Fouling of heat exchange surfaces by:	
	(*a*) Asphaltic solids	Oxidation and other chemical action.
	(*b*) Soaps	Action of organic acids on metals.

For the sake of completeness, mention is made of a possibility that transformer oil during use may be adversely affected by electrical stresses. Any chemical or pertinent physical change seems unlikely except in cases of puncture when such a change would be effect rather than cause.

The subject of suitable methods for durability tests of transformer oils is now being studied by Committee D-9 on Electrical Insulating Materials through a sub-committee made up of three mutually interested groups: the transformer manufacturers, the consumers of transformer oil and the transformer oil producers. Although the information acquired is not yet ready for publication it seems desirable to call attention to this investigation, which is outlined in the report of the committee, and to indicate in a general way the purpose, the factors involved and some of the possible solutions of the problem. The expression "sludging tests" often used in connection with transformer oils has been rejected in this paper as too specific in scope and has been replaced by the broader and more applicable term "durability tests." Such tests are therefore intended to determine by laboratory work in a reasonably short time whether after long use in a transformer an initially suitable oil will still retain the ability to perform safely its double function as an electrical insulator and as a medium for dissipating heat. Of all the essential tests for transformer oils, it may be said without fear of contradiction that those concerned with durability are the most difficult of execution and the most obscure in interpretation.

Having in mind the statements already made, it seems logical to apply direct durability tests to transformer oils by accelerated oxidation of the fresh oil in the laboratory and examination of the reaction products for dielectric strength, resistivity, viscosity change, organic acidity, sediment and other components. Three types of oxidation tests for transformer oils are described in the literature but the directions given are not so definite and precise as those required in A.S.T.M. methods.

The least indefinite of these three tests as to details is the Michie test used by British engineers. The fresh transformer oil is oxidized at a temperature of 150° C. by a current of air bubbled through the oil for 45 hours in the presence of copper as a catalyst. The resulting oxidized oil is then examined for substances insoluble in petroleum naphtha and the result is reported as per cent by weight of sludge or solid matter. Oils showing the lowest percentage of sludge are assumed to be most durable in service.

A second oxidation method is the resinification test used by German engineers. In this case the oil is oxidized at 120° C. by a current of oxygen bubbled through the oil for 70 hours, no catalyst being used. The acid compounds formed are then separated by appropriate chemical means and their percentage by weight is used as the index of resinification. Oils showing the lowest percentage of resinification are assumed to be the most durable.

A third type of oxidation method used largely in France consists in heating the oil in an open glass container for a designated time at a designated temperature, with or without a catalyst as required. The resulting product is then examined for sediment and sometimes for color change. The Waters carbonization test designed primarily for lubricating oils is somewhat similar but much more clearly described. It is evident that durability tests for transformer oils are very closely related to those for lubricating oils, conspicuously turbine oils. Development in either field will be of mutual advantage.

The results obtained in duplicate determinations on the same oil by any one of these methods show discouraging variations. Much more disconcerting, however, are the conclusions drawn from results by different methods as to the relative durability of two or more transformer oils. For example, the following figures indicate the absolutely contradictory results on two American transformer oils:

	MICHIE TEST, BRITISH.	RESINIFICATION TEST, GERMAN.
Oil No. 1...	0.9 per cent sludge or solid matter	0.1 per cent organic acids
Oil No. 2...	0.04 per cent sludge or solid matter	6.0 per cent organic acids

It appears impossible in this case to select the more durable oil except by the toss of a coin or by national favoritism.

Three other methods suggested for durability tests on transformer oil are somewhat indirect since permanence of quality is predicted according to the proportion of so-called unsaturated hydrocarbons present in the fresh oil. The value of these tests is not definitely known but two of them present interesting possibilities.

The "Deposit Test," often called the "Formalite Test," is based on the fact that under suitable conditions formaldehyde will combine chemically with unsaturated petroleum hydrocarbons forming a solid material which may be separated and weighed.

Another method consists in determining iodine addition values and iodine substitution values of the fresh oil by an improved procedure recently described.[1]

A third indirect method is the venerable sulfuric acid absorption test which is usually conceded to mean nothing, though it still finds a place in a Federal specification for transformer oil.

Without further mention of the numerous other durability tests proposed, it seems quite evident that the subject needs further study, not only diligent but also intelligent. There is a woeful lack of positive and authentic information correlating laboratory tests on fresh oil with the service life of the same oil. While the marked disagreement between British and German engineers may not be surprising, it is certainly embarrassing from a scientific standpoint. Although American engineers in a general way favor the British point of view, this is probably due to historical development. At any rate, the American engineer is not taking a positive stand in the matter without more information and his ultimate conclusion as to durability of transformer oil is quite likely to depend on the work of Committee D-9, supplemented perhaps by results soon to be published by British investigators.

In summarizing the paper, attention is called to the following points:

1. Transformer oil derived from petroleum is a necessary adjunct to economic development and will become even more important in the future.
2. Initial suitability of a transformer oil depends on its ability to dissipate heat generated in the transformer and to provide necessary electrical insulation at the same time.
3. Durability tests are necessary to indicate whether the initial suitability will be maintained even after prolonged use.

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[1] E. M. Johansen, *Journal, Industrial and Engineering Chemistry*, Vol. 14, p. 288 (1922).

4. Deterioration of the oil during service is due chiefly to oxidation yielding solids and viscous liquids which retard circulation, water which lowers dielectric strength, and acid bodies which do both.

5. Durability tests may be direct, involving examination of oxidized oil, or they may be indirect, being measurements of supposedly unstable constituents.

6. In conclusion, it may be said that the outlook is bright for a reasonably satisfactory durability test or tests on transformer oil, through the cooperative work of Committee D-9 on Electrical Insulating Materials. Suggestions and criticisms will be welcome, particularly from electrical engineers, but they should be submitted promptly as the necessary investigation is well under way.

DISCUSSION.

Mr. Herschel. MR. W. H. HERSCHEL.—The situation that exists in regard to the testing of the durability of transformer oils is not essentially different from the situation in regard to the durability of lubricating oils. The causes for deterioration in use are very similar. In the table on page 534, 1 (*a*) and 1 (*b*) would apply equally well to lubricating oil. That is certainly one of the most important causes of deterioration of a lubricating oil in use—oxidation. The difficulty is that, as in transformer oils, there is no unanimity of opinion as to what is the best test to determine the durability of a lubricating oil in use. The tests which have been proposed and used to some extent are the emulsion test, the carbonization test of Waters, which is really an oxidation test, the Conradson Carbon Residue Test, which is a cracking test, and the test for organic acidity, because organic acid develops as the oil oxidizes. But we have the same case as in the table at the bottom of page 535. We find that, as a general rule, if you use the Waters Carbonization Test, the numerical value decreases as the viscosity increases, whereas if you use the Conradson Carbon Residue Test, then the numerical value increases as the viscosity increases. It is perfectly evident that these two tests determine different properties of the oil, but it is not evident which is the more valuable test or which test should be given the greatest reliance. It may be that under certain circumstances one test should be used and under other circumstances another. Take, for example, the case of an automobile oil. It may be that one test is of more value in regard to the formation of so-called carbon deposit in the cylinder, and that the other test is of more value in regard to the formation of sludge in the crank case. The whole subject requires further investigation, but I think we do know this, that oxidation is probably the most potent cause for the deterioration of an oil in use. The refiners have not settled upon any one test which they will agree is the test by which their oils should be judged. The result of the lack of a durability test, approved by the refiners, has had but one result and can have only one result, and that is, that the public, the consumers, who demand a test for durability, will not be satisfied with nothing, and what they do, and what they must inevitably do as long as this condition exists, is to put into the specifications any test which gives the faintest hope of being the long-sought-for test which will insure that the oil will show durability in service.

Mr. Rather. MR. J. B. RATHER.—Mr. Delbridge made no mention of the American practice in testing transformer oils for oxidation, and I should think that the practice of the General Electric Co. would be of interest in this connection. It seems to me that the American practice of making this test is at least of equal importance to the English and German practice, and in our own experience, which has included the Michie test, the General Electric test and the German Test, has been that the American test, whatever the objections there are to it, is at least a reproducable test, and that's more than I have been able to find as far as the Michie test is concerned.

Mr. Delbridge. MR. T. G. DELBRIDGE.—Mr. Chairman, I will answer the question by taking exception to calling the General Electric test the American test. It is an American test, but it would hardly seem fair to say that the General Electric Co. test, which has been modified several times and will probably be modified several times more, is the American test, when another large company, the Westinghouse, is currently using the deposit test. I had no thought of ducking the issue by neglecting the American test, but there isn't any test that can be recognized as an American test—there are several. The General Electric test, is, as I see it, really a modification of the Michie test. As far as duplicating the determinations on the same sample, it is only necessary to keep the conditions fairly uniform and fairly uniform results may be obtained by any one of the methods mentioned. When I say fairly uniform I mean differences of possibly 10 per cent of the average result which is good for a sludge test. I think that can be done without a bit of trouble by any laboratory that will follow the directions that have been put out to the members of the Sub-Committee of Committee D-9 in the work they are doing. The trouble is that a very slight modification in procedure makes a very big difference in results. Often the change is so slight we are almost ready to say we didn't make any change, yet we know we did because we have certain variations. That's the reason I don't want to get the idea in the minds of people here that there is any such thing as an American test. There isn't yet.

The Chairman. THE CHAIRMAN (MR. F. R. BAXTER).—So far as variations are concerned, the British Engineers' Standard Board, which adopted the Michie test, has at a recent session, where the limit was put at 0.05 per cent of sludge, allowed a 100 per cent variation.

Mr. Hanson. MR. C. F. HANSON.—In the manufacture of paper insulated power cables, petrolatum is generally used as an impregnating compound. Petrolatum is similar to lubricating oil and transformer oil in at least one respect. It oxidizes when it is heated and exposed to

Mr. Hanson. air. When petrolatum oxidizes it deteriorates as an electrical insulator. One electrical characteristic which is particularly sensitive to the oxidation of petrolatum is its electrical resistivity. Its resistivity drops off very rapidly and definitely as oxidation goes on. I am of the opinion that a similar relation exists between the resistivity and the oxidation of transformer oil. This method of measuring oxidation ought to be worth considering because of the possibilities which it offers.

The resistivity measurements are not difficult. A method for making this measurement is briefly described in a paper published by Del Mar and Hanson in the *Journal* of the American Institute of Electrical Engineers, Vol. 41, p. 439, June, 1922. The title of the paper is "Effects of the Composite Structure of Impregnated Paper Insulation on its Electric Properties."

METHODS FOR CONDUCTING PHYSICAL TESTS ON RUBBER PRODUCTS.

By A. H. Nuckolls.[1]

The value of rubber products produced annually exceeds a billion dollars. This enormous output is for thousands of different uses, and there are possibilities for a great many new uses. The chemist and engineer have played an important part in developing this great industry. They have been of increasing service to both manufacturers and users in establishing and standardizing methods of test that have been an important factor in the improvement of the quality of the output, in the manufacture of new products to fill long existing demands, and in enabling users to better specify the product needed.

The testing of rubber is not a simple matter and unless intelligently applied may give misleading results. Experience and general knowledge of rubber are essential to have the interpretation of test results of practical value. Even the testing operations as such involve factors which influence the results. Probably the method of test is of greater importance in the testing of rubber products than in the case of any other common article of commerce. This applies both to chemical and physical tests.

It is not intended to attempt to add anything new to the subject but to briefly present the fundamental factors relating to the four physical tests most generally applied under purchase specifications: (1) the tensile strength or ultimate strength, (2) stretch at break or ultimate elongation, (3) recovery or set, and (4) friction or adhesion between the rubber and fabric.

In specifications including the above tests, the limits applied should be based upon the nature of the compound and its intended use. Specifications built up without a knowledge of rubber compounding and properties of rubber obtained by tests, as well as of service requirements, are likely to be worse than useless, and to embarrass both manufacturer and user. It is essential that test methods for determining the limits specified should be referred to.

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[1] Chemical Engineer, Underwriters' Laboratories, Inc.

PREPARATION OF TEST SPECIMENS.

Factors Influencing Results.—The methods of preparation of specimens for physical tests are not free from difficulties and are as important as the subsequent tests. Owing to the diversified character of rubber products from which specimens are prepared, there is no particular method generally applicable, but the fundamental factors which may influence the results apply in all cases, and include surface injury, mechanical working, heating, and the form and dimensions of the specimen.

Surface Injuries.—Surface injury is probably the most important factor mentioned above. The tendency of rubber when under stress to tear at any point where there is a scratch or nick is characteristic, and it is essential that the method of preparation be designed to avoid injury to the specimen, particularly at its edges. In cutting specimens to a test form, as shown in Fig. 1, the use of a steel die will prevent rough edges. Gasoline should generally be used in separating rubber from layers of fabric. The action of the gasoline softens the friction compound, enabling the operator to remove the rubber without subjecting it to much stress. When applied from the fabric side in small quantity it will thoroughly evaporate, if free from objectionable oils. To avoid injuring the surface of the specimen, gage marks for reference in determining the elongation are best applied by means of a metal stamp having parallel blades.

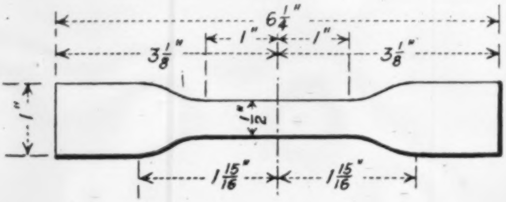

FIG. 1.—Tension Test Specimen.

Mechanical Working and Heating.—The effect of mechanical working is discussed later in connection with the influence of previous stretching. Heating occurs when a buffing operation is required in preparing the specimen and must be prevented by carefulness in order to prevent permanent injury to the rubber.

Size and Form of Specimen.—The sectional area is theoretically not a factor in the unit values obtained in the tension and stretch tests but in actual practice small specimens are likely to give higher results. The form of specimen now generally used in the case of rubber proctsdu made from calendered sheets is shown in Fig. 1. This has a reduced section at the center 2 in. long and 0.5 in. wide. The ends are enlarged to avoid breaking the specimen in the grips. Test analysis of this form by placing parallel lines on the ends lengthwise of the specimen and applying tension, show that very little cross stress results on account of the enlargement of the ends. A specimen of similar form having a reduced section $\frac{1}{4}$ in. wide at the center is employed where it is necessary to use a small sample, but the larger test specimen is preferable.

Ring Specimens.—Ring specimens are not usually available for tests of the finished product and have the disadvantage that the tension is not uniformly distributed, resulting in cross stresses.

Tubular and Tangential Specimens.—In case of rubber-covered wire, No. 6 gage and smaller, having a solid conductor, tubular test specimens give the best results provided the conductor is removed without injury to the rubber. Usually this can be accomplished by first stretching the conductor to its breaking point to reduce its diameter, but in some cases the rubber adheres to the stretched conductor, in which case the use of mercury is desirable. This is employed by allowing the specimen to remain submerged for about an hour, after which the rubber can generally be easily pulled from the conductor. In the case of stranded conductors when individual wires cannot be removed without injury to the rubber, a split tubular sample may be employed. Tangential specimens have the disadvantage of being difficult to prepare and measure.

Measuring the Thickness.—Measurements of thickness of specimens or in the case of tubular specimens the diameter over the rubber should preferably be made with a dial micrometer provided with a circular shoe operating under a standard pressure. By removing the spring that is usually supplied with such an instrument and attaching a disk, the load can be applied by placing the required weight on the disk. Such an instrument has the advantage that it does not require calibration.

Mechanical Working.—Previous stretching within certain limits temporarily increases the tensile strength, stretch, and recovery to an appreciable extent, but on repeated stretching the rubber begins to break down. These effects vary with different compounds and have not been thoroughly worked out.

Effect of Backing.—In cotton rubber-lined fire hose, a rubber cementing compound known as the backing is used to obtain adhesion between the rubber tube or lining and the cotton jacket, and at the same time to fill the interstices between warps and fillers in the fabric to prevent corrugations in the lining. The backing usually has a lower tensile strength, stretch and recovery than the rubber tube, and if not removed retards the stretch and recovery. If included in the cross-sectional area of the specimen, it reduces the tensile strength.

Direction of Cutting.—Rubber products made from calendered sheets have a greater strength and elongation in the direction in which the rubber was rolled; that is, longitudinally. But the performance in the recovery test is better when the specimens are tested transversely; that is, across the direction of rolling.

INFLUENCE OF TEMPERATURE.

The temperature of the specimen at the time of test is a factor generally recognized as influencing the results. Usually, through the range 60 to 90° F., the tensile strength decreases as the temperature increases and the amount of stretch at break may increase as the temperature rises. Within this range the performance in the recovery test is usually better at about 80° F. Different rubber compounds are not affected by temperature, particularly in respect to the stretch, to the same extent, and it is believed to be impracticable to satisfactorily employ a correction factor. The results of a series of tests conducted at the Underwriters' Laboratories is presented in Fig. 2.

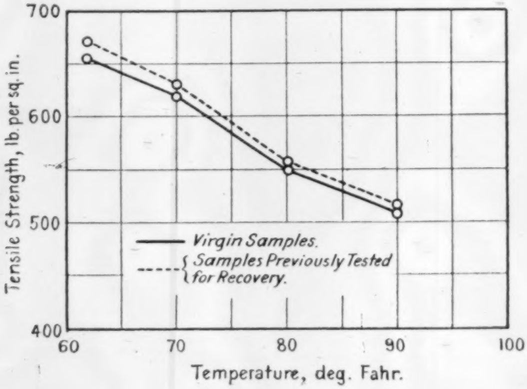

FIG. 2.—Effect of Temperature on Tensile Strength.

Each point on the curves represents 3 tests on each of 14 compounds, and is therefore an average of 42 determinations.

The effect of temperature on the stretch varies more with different compounds than does the tensile strength, which may be roughly taken, in the case of vulcanized compounds, as 1 per cent loss per 1° F. rise in temperature within the range 60 to 80° F., although the effect on the tensile strength and stretch is somewhat greater through the range 70 to 80° F. than between 60 to 70° F. In the case of compounds containing unvulcanized rubber, such as those used for tape, the temperature effect is much greater. For the average compound, 70 to 73° F. appears to be the temperature at which standard tensile strength, stretch and recovery values are best obtained. Above 70° F., the temperature effect usually begins to increase.

As rubber is a poor conductor of heat, some time should be allowed for specimens to reach the temperature of the testing room. Where the difference in temperature does not exceed approximately 50° F., one to three hours appear to be sufficient in the case of small specimens. The results of two series of tests conducted at the Underwriters' Laboratories in a testing room at a temperature of 70° F. showed no material changes in the performance of specimens on increasing the interval from 1 to 24 hours from the time the samples were brought in from an outside temperature 50° F. higher in one case and 50° F. lower in the other. The results are presented in Fig. 3.

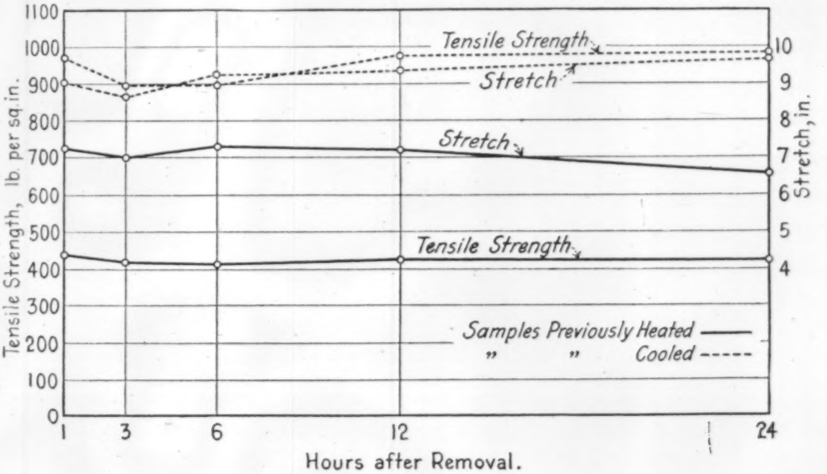

FIG. 3.—Results of Tests to Determine the Length of Time Required for Specimens to Reach Room Temperature.

In the first series of tests, the samples were heated 18 hours at a temperature of 120° F. and subsequently tested after 1, 3, 6, 12, and 24-hour intervals of rest at 70°. In the second series of tests, the samples were at 0° F. for 72 hours. These samples do not represent all the types of rubber compounds met with in practice but indicate that in general, the lag in the change in the tensile strength and stretch with temperature is practically negligible after 2 hours. Cases have been reported by other observers where peculiar compounds were encountered having a lag exceeding 18 hours.

INFLUENCE OF RATE OF SEPARATION OF THE JAWS.

The speed at which the jaws of the testing machine are separated determines the rate at which the rubber is stretched but not entirely the rate of application of the load. While the rate of stretch is directly proportional to the speed of separation of the jaws, the rate of application of stress depends also on the nature of the compound. In other words, the stress required to produce a given elongation varies with the compound.

The influence of the rate of separation of the jaws on the breaking strength is the resultant of these two factors. In general, the resultant is usually toward higher values for both tensile strength and ultimate elongation as the speed of the jaws increases, but varies with different rubber compounds. Within practical limits it seldom amounts to much.

In the testing of rubber, the elongation factor has been eliminated by the general adoption of a standard speed of stretching of 20 in. per minute, which is not only convenient but satisfactory for practical test purposes. This does not eliminate the variable which depends upon the rate of applying the stress as that factor also depends upon the compound. It will be a constant in any series of tests of a given lot of rubber.

FRICTION TESTS.

In friction tests, the effect of temperature is the principal factor in the test conditions influencing the results. The rate of separation between layers of fabric and rubber when subjected to tension is not proportional to the load applied. No separation may occur up to a certain point on increasing the load, after which the rate of stripping may increase very rapidly with additional loading.

Two methods of test are in general use. In the case of air and steam hose, the test specimen is fitted on a mandrel and one end of the fabric separated from the rubber to permit attaching a grip from which a prescribed weight is suspended vertically and the distance through which separation of the rubber and fabric takes place in a given time is observed.

In the case of fire hose and belting, one separated end of the fabric is clamped in a stationary grip and the other end in a suspended grip attached to the prescribed weight hanging vertically. In the latter case, the angle of separation is less than in the tests with a mandrel and the test is somewhat more severe for a given load.

TESTING MACHINES.

Tensile Strength and Recovery.—The machine used for tensile strength and elongation tests should be power-driven and of the inclination-balance or pendulum type except that when the loads are small, say under 50 lb., a spring balance type may be used if provided with calibration apparatus and a dead pointer or other device which will register the maximum load obtained. Movable elongation pointers provided with a graduated scale are essential. When the machine is operated, the jaws should separate at a speed of 20 in. per minute regardless of the load. The accuracy of the readings should be within ±1 per cent. The grips must be of a type which exert a uniform pressure on the specimen and tighten as the tension increases. Grips of the eccentric disk type are well adapted for testing specimens with enlarged ends. Grips of the type which consist of two steel rolls, give very good results in the testing of tubular specimens.

Machines for autographically registering the tension and elongation would be very desirable. The principal difficulty encountered in attempting to perfect such an apparatus is in the design of a grip which will entirely prevent slipping of the specimen, in order that the distance of separation of the jaws may accurately show the exact elongation of the specimen.

ACCELERATED AGING TESTS ON RUBBER GOODS.

By W. W. Evans.[1]

The most prominent problem that has confronted the rubber chemist has been the prevention of deterioration of vulcanized rubber with age. Dealing as we do with a perishable vegetable material, there is no problem quite so important to the manufacturer and the consumer as the too rapid change in physical properties on standing. On account of this change in vulcanized rubber it has become common practice to build into various compositions excess properties beyond the real needs of service, in order to make allowance and leave after a period of time sufficient quality to withstand the service for which the articles were designed.

The first work done in the laboratories of the B. F. Goodrich Co. on accelerated aging tests was begun in the Fall of 1907 by Dr. W. C. Geer. He decided that the first step in the solution of this problem was a means by which the rate of deterioration could be predicted. Even though a knowledge of means of preservation was lacking, it would be at least possible to handle various materials entering into rubber goods so that the maximum life could be determined. This led to the study of accelerated aging tests and the final development of the one described in this paper.

Full references to all the earlier work on this subject are contained in a paper presented before the International Rubber Congress at London in June, 1921. This paper appeared in the *English India Rubber Journal*, June 11, 1921, and was later reprinted in the *India Rubber World* under date of September 1, 1921.

After carrying on numerous experiments at different temperatures and after varying the periods of time, Geer found that 160° F. gave the most satisfactory results. Upon the basis of this work, the following procedure has been adopted and used in carrying out several thousands of such tests.

Into an oven, heated air was blown at a temperature of 160° F., care being taken to see that a continuous supply of hot fresh air was added during the entire aging period. A number of samples, $\frac{3}{32}$ in. in thickness, were previously cut in the form of our standard test strip and placed in this air bath. As may be noted in Fig. 1, the test strips are suspended by punching a hole in the enlarged end, passing a wire through and placing between each strip a rubber disk which is about the same thickness as the test piece to keep the individual strips separated and allow a free circulation of air so that the entire surface is exposed.

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[1] Development Manager, The B. F. Goodrich Co.

The air was then started circulating and the test continued for a period of two weeks, taking out three samples each day. These were allowed to stand for twenty-four hours at room temperature until they reached a state of equilibrium, after which they were tested for tensile strength and elongation.

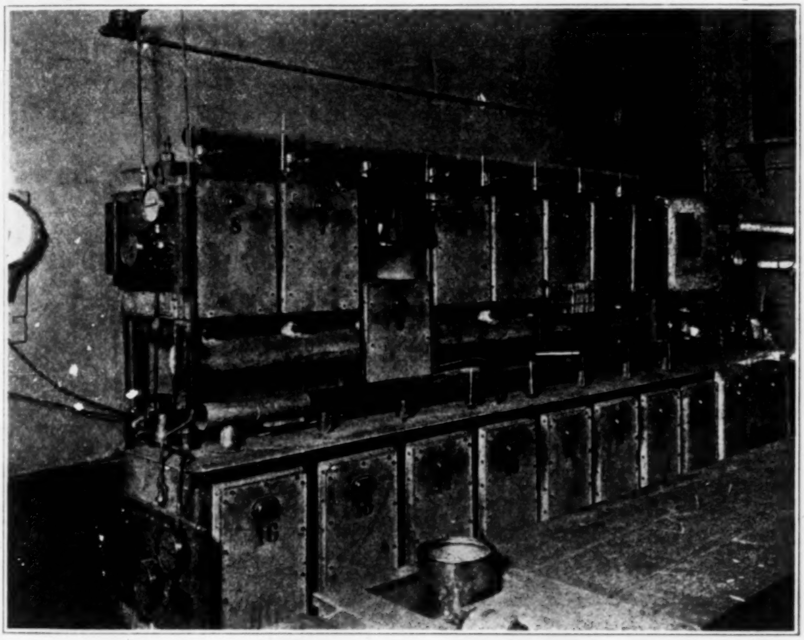

FIG. 1.—Ovens for Accelerated Aging Tests.

While a particular type of oven in which to perform these aging tests has been referred to, where a lesser number of tests are to be made and where a standard type of electric drying oven is available, this can be adapted to such work provided a mechanical agitator is placed inside the oven to insure an even temperature throughout, and a constant supply of fresh air heated to 160° F. is maintained throughout the test. As an example of one of these electric ovens, the type known

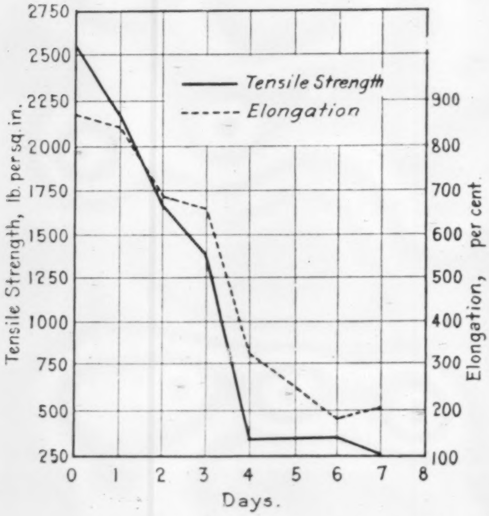

FIG. 2.—Accelerated Aging Test on Rubber Thread.

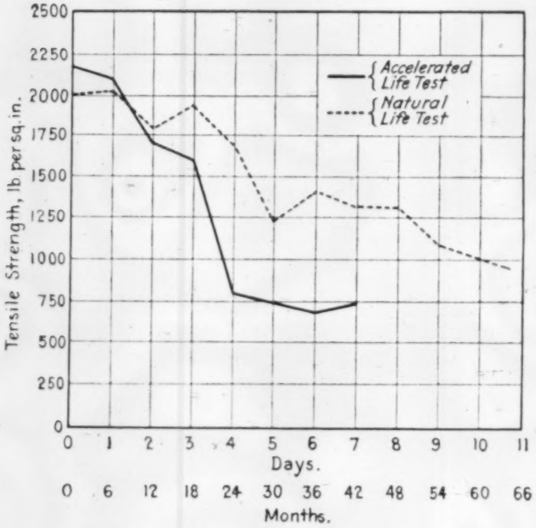

FIG. 3.—Comparison of Accelerated Aging and Natural Life Tests on Rubber Threads

as the Freas, equipped with an electric agitator on the inside of the oven, has proven most satisfactory.

The data plotted in curve form give a time-decay curve of the compound. For a long time the tests were always run in comparison with a standard compound, that is, at least two sets of samples were run at the same time. Thus, by comparing the curve of a compound the age of which we knew, and the curve of a compound which we did not know, we obtained a reliable indication of the service to be expected from this new compound. It is worth while to point out that we consider this purely a practical and not an ultimate test. Our experience, however, based on many thousands of these curves indicates that this method of determining the approximate aging of a commercial rubber product is reliable, and is of great value as an aid to a compounder in a manufacturing plant, permitting him to study the aging of varying compositions.

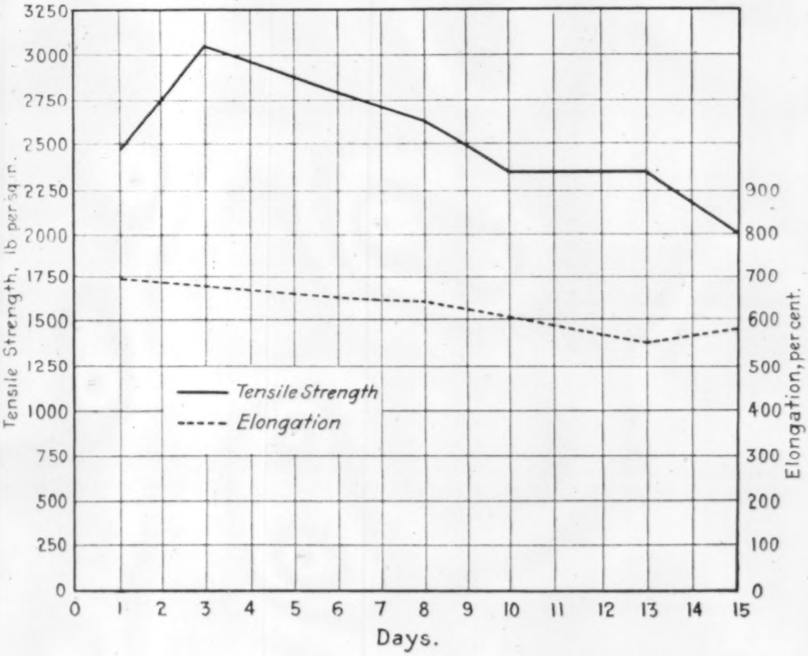

FIG. 4.—Accelerated Aging Test on Pneumatic Tire Breaker Strip Friction, Cured for 60 minutes at 294° F.

No attempt has been made until recently to determine the probable chemical reactions involved. It seems reasonable to assume, however, at the temperature employed and with a current of fresh air passing over the samples, that oxidation occurs, forming one of the unstable peroxides and at the same time causing an increase in the coefficient of vulcanization, similar to that resulting from the aging of rubber under normal conditions.

A few of the curves, taken from the records of the laboratory, have been selected which illustrate certain typical characteristics and of which natural aging data were available. The compound used in Fig. 2 is one of the older types so common in rubber thread. This curve shows the change in the elongation and in the tensile strength over a period of seven days. The curves are sharp and the deterioration was rapid. Fig. 3 shows the decay of the same compound, but of different cure. The heavy line is the curve plotted from the data taken from the strips that had been exposed in the aging cabinet. The broken line is the plot from data obtained from strips that had been filed away in a dark room kept at ordinary temperatures and in the dark, and test strips removed at intervals over a period of a little more than five years. From these curves, it is to be seen that the accelerated life test is somewhat more severe than the natural life test, although there is some degree of correspondence in the general shape of the curves.

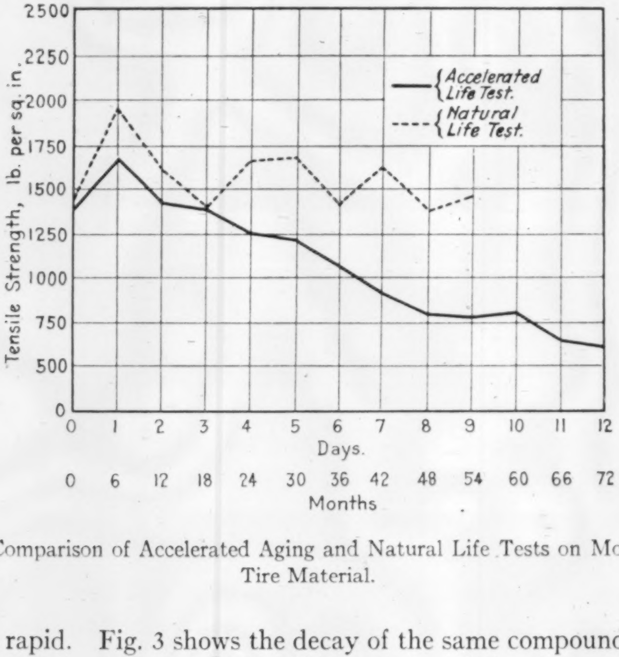

FIG. 5.—Comparison of Accelerated Aging and Natural Life Tests on Motor Cycle Tire Material.

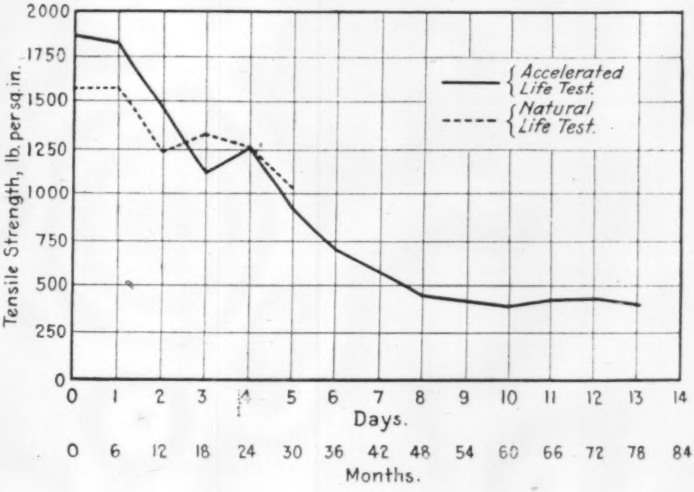

FIG. 6.—Comparison of Accelerated Aging and Natural Life Tests on Air Brake Hose Material.

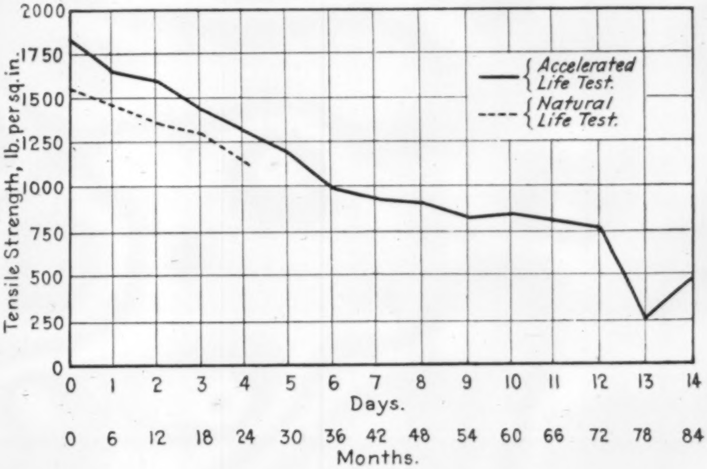

FIG. 7.—Comparison of Accelerated Aging and Natural Life Tests on Solid Truck Tire Material.

Fig. 4 shows a different compound and a different cure, and shows a wholly different type of aging curve. In this case, the tensile strength and elongation have remained at high levels, and one would judge this compound to be a good one. In point of fact it is a remarkably good one, and while we cannot show the curves from natural life it has stood the test of time in a highly satisfactory manner.

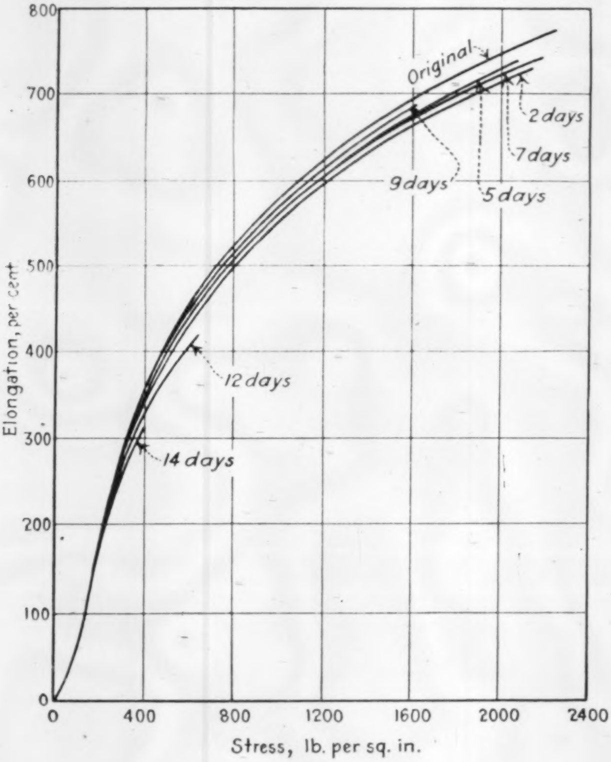

FIG. 8.—Stress-Strain Diagrams in Accelerated Aging Tests. Inner Tube Material.

In Fig. 5 have been plotted data from the natural and short life tests for tensile strengths only. The compound is one of the older type composed of natural grades of rubber and litharge as the accelerator. The accelerated life test again shows more severe than the natural aging. These curves may be considered typical, and one of the general conclusions may be anticipated at this point, which is that when an accelerated aging curve shows a type where the tensile strength is nearly constant for the first three or four days and following that shows no severe decline, it is usual to find the natural life test to be at least as good, and usually better. Experience in judging curve data is necessary in comparing unknown with known compositions before any considerable volume of output may be predicated upon uncompared data.

Fig. 6 shows a relatively close comparison of accelerated and natural life tests of a lower grade composition.

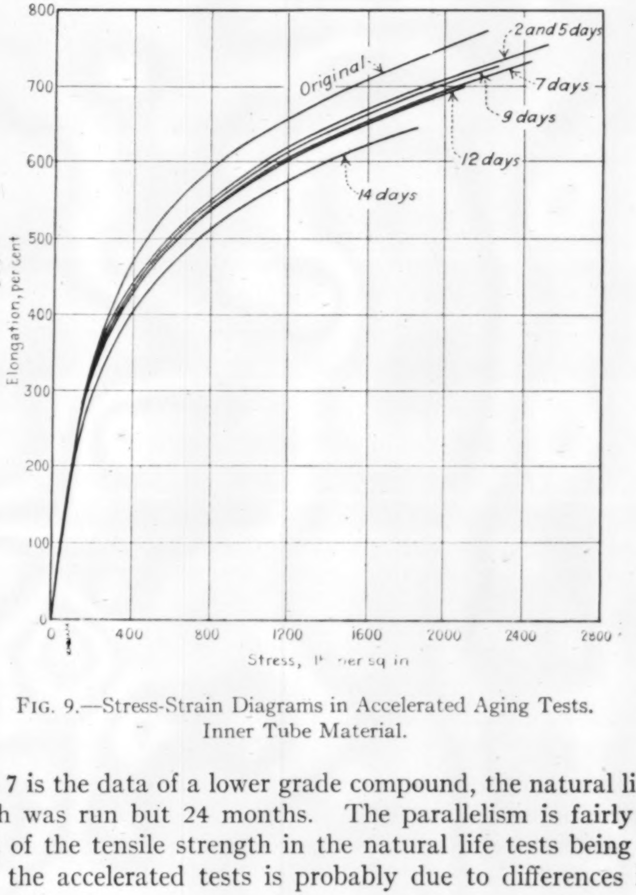

FIG. 9.—Stress-Strain Diagrams in Accelerated Aging Tests. Inner Tube Material.

Fig. 7 is the data of a lower grade compound, the natural life test for which was run but 24 months. The parallelism is fairly close. The fact of the tensile strength in the natural life tests being under those of the accelerated tests is probably due to differences in the original mixings.

Fig. 8 illustrates the effect of the test upon the stress-strain diagrams. The compounds are of the inner tube variety, that is to say, composed of rubber, sulfur and accelerator. This figure is of a high grade type and shows high resistance to aging. There is, as will be observed, but little change in the form of the curves. The compound has become stiffer and weaker.

In Fig. 9 is shown the results of the aging test upon a similar compound, but which resisted the effect of the heating to a lesser degree than the one shown in Fig. 8. There is very little that we can say regarding the effect of aging on the stress-strain curves. Our work has had to do more largely with the effect upon that more basic property, tensile strength.

CONCLUSIONS.

The results of several thousands of tests show that the accelerated test has proved to be a valuable means of approximately predicting the relative rate of deterioration of rubber compounds. In a general way the following conclusions were drawn:

1. We consider it more reliable to plot curves and compare them than to consider the percentage deterioration from the original tensile strength.
2. The samples in the accelerated aging test are not hardened as in actual aging, but are definitely weakened.
3. Sulfur changes are noticeable, but not important.
4. Despite the fact that the curves of accelerated and natural life tests are not exactly parallel, the accelerated life test is somewhat more severe in general than the natural life.
5. In the vast majority of cases, too rapid deterioration of rubber compounds is due to over or under cure, and chiefly over cure, than to any one or more compounding ingredients. The test has been of utmost value in indicating the proper cure. Troubles with organic accelerators, various grades of unfamiliar crude rubber, mineral fillers of various kinds, and so on, have been due chiefly to attempts to graft a new material upon an old practice and often with fatal results.
6. This test is a comparative and not an absolute one and should never be used to compare compounds of different type.
7. When used properly, there has been found to be an approximate correspondence between accelerated life and natural life tests after four days in the oven, of one day equalling six months.

A RATIONAL BASIS FOR COAL PURCHASE SPECIFICATIONS.

BY E. B. RICKETTS.[1]

Before undertaking to write a set of specifications for the purchase of coal for any given plant, a thorough investigation should be made of the facilities for burning, handling and storing coal, for handling and disposing of refuse, the load conditions, and the relation of load to be carried to capacity of coal-burning equipment. In addition to investigating the plant conditions a study should be made of all the coal producing districts whose location would make them possible sources of fuel supply.

In order to illustrate the method of selecting the most suitable coal for any given plant let us consider in detail this problem from the point of view of a large public utility operating steam power plants for the supply of electric light and power in New York City. These plants are situated along the waterfront, some of them have facilities for handling coal either from ocean steamer or river barges while others, on account of lack of sufficient depth of water, can accommodate only river barges. Ashes must either be hauled considerable distances and used to fill swamp land or barged out to sea. In any case the disposal of refuse is an item of considerable expense. These plants are equipped with underfeed stokers and have a load varying through wide limits, being subject to sudden thunderstorm peak loads of considerable magnitude that make necessary the operation of the boilers at heavy overloads during periods of maximum demand.

In undertaking the study of the sources of coal supply for these plants, a map showing the location of coal deposits, such as the one contained in *Professional Paper 100-A*, U. S. Geological Survey, together with the bulletins of the U. S. Bureau of Mines, giving the analysis of coal samples from the various coal fields and the coal freight schedules will be found very useful.

A study of the above documents will show that there are three general classes of coal which are so situated as to be able to compete in the New York market. These are:

1. The anthracite coals of eastern Pennsylvania;
2. The semi-bituminous coals of Pennsylvania, Maryland and the Virginias;
3. Part of the Pennsylvania bituminous coals.

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[1] Assistant to Chief Operating Engineer, The New York Edison Co.

On account of its desirability as a domestic fuel the sizes of anthracite coal larger than No. 3 Buckwheat are too high in price to be attractive for use in power plants. The reports of the U. S. Geological Survey indicate a probable production of about ten million tons per year of No. 3 Buckwheat for the next ten years. Of this amount about seven and one-half million tons are used at the mines, leaving about two and one-half million tons available for sale. As the plants under consideration would require two million tons per year it is obvious that there is no adequate supply of this fuel available.

The laws of New York City prohibit the emission of smoke. It is much more difficult to burn bituminous coal than the less volatile semi-bituminous coals without objectionable smoke. There are rarely any price differentials or other advantages of sufficient importance to compensate for the additional trouble and expense necessary to burn bituminous coal smokelessly. Consequently, it can be eliminated from consideration.

The semi-bituminous field which stretches in a narrow belt from northern Pennsylvania to West Virginia presents many locations from which may be obtained coal which will burn smokelessly and with high efficiency on underfeed stokers. These coals are located in four states and can be shipped over a number of widely separated railway systems, thus giving good assurance that the coal supply will never be completely interrupted.

Having decided that the coal supply is to be drawn from the semi-bituminous field, it remains to select that coal possessing the characteristics most desired. Experience in the operation of the plants under consideration has shown that the most satisfactory results can be obtained from coals having the following characteristics:

1. A volatile content less than 20 per cent;
2. As low ash as possible;
3. An ash fusion temperature not less than 2450° F.;
4. At least 25 per cent of the coal should be capable of being stored for nine months without serious trouble from spontaneous combustion.

The first three items given above can be determined in a chemical laboratory. For the fourth, experience is so far our only guide.

Having selected from the coals offered those which from consideration of price, quality, etc., seem to be most suitable, sample cargoes of these coals are obtained and subjected to a boiler test which weeds out a number of coals which laboratory tests may have indicated would be satisfactory.

We now have before us a number of coals offered at various prices all of which our tests indicate will give satisfactory results in the boiler room. It still remains to determine their relative value. The factors which determine the value of any coal in any given plant are as follows:

1. The cost in the bunkers of the coal required to produce a given number of British thermal units in the steam;
2. The relative investment in boiler plant, including coal and ash handling machinery, land, buildings, etc.;
3. The cost of handling and disposal of refuse;
4. The relative cost of fire room labor with coals differing in quality;
5. The cost of carrying banked boilers varying with the quality of the coal;
6. The clinkering tendencies of the coal.

All of these factors with the exception of No. 6 bear a very definite relation to the percentage of ash in the coal and an attempt has been made in the accompanying curves (Fig. 1) and formulas to give a method by means of which a comparison can be made of the value of a coal of any given analysis and that of a coal containing 5 per cent of ash. In this curve no account has been taken of the effect on coal value of extra fire room labor (other than that involved in handling and disposal of ashes), extra cost of operating banked boilers or clinkering tendencies of the ash. The reason for this is that the first two of these items in most plants is a very small proportion of the total effect on coal value of changes in ash percentage and in the case of the third item there is a lack of definite data applicable to other than a very restricted type of coal-burning equipment.

The curves given on this sheet are based on experimental data obtained at the plants of the New York Edison Co. and the Union Electric Light and Power Co. at Cincinnati, Ohio. Both of these plants are equipped with an underfeed type of stoker, the first being equipped with low-set boilers and the second having a modern type of setting. These curves are the average of the experimental data of the two plants and represent the conditions to be expected in the average underfeed stoker plant.

Two sets of formulas are given for applying these curves to all conditions; the first set takes into account the relative coal cost of a given number of British thermal units in the steam plus the cost of ash handling and removal, and the second set in addition to the items considered in the first set take into account the cost of extra investment necessary in boiler plants to burn the higher ash coal.

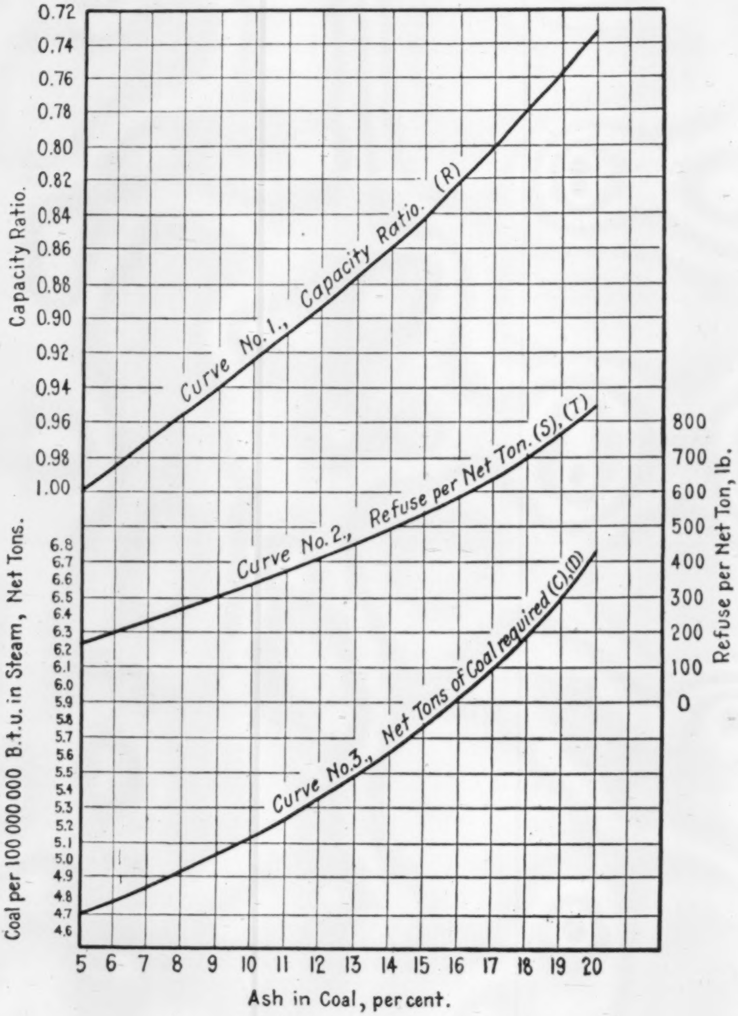

FIG. 1.—Relation of Cost Factors and Percentage of Ash Coal.

Examples are given, showing the application of these curves and formulas to various plant conditions.

FORMULAS FOR USE IN CALCULATING COAL VALUES.

Three thousand boiler horse power maximum rating will produce 100,000,000 B. t. u. in steam per hour. If the boiler plant, including land, buildings, etc., cost \$100 per maximum horse power when using 5-per-cent ash coal, then such a plant would cost \$300,000, which at 15 per cent (interest 7 per cent; depreciation, 6 per cent; taxes and insurance, 2 per cent) equals \$45,000 per year, or \$5.13 per hour.

Let X = Cost in dollars per net ton of 5-per-cent ash coal in bunkers (exclusive of ash handling);
Y = Value in dollars per net ton of x-per-cent ash coal in bunkers (exclusive of ash handling);
A = Load factor;[1]
B = Cost of boiler plant per maximum horse power divided by 100;
Z = Value in dollars per net ton of x-per-cent ash coal in bunkers;
C = Tons of 5-per-cent ash coal to produce 100,000,000 B. t. u. in steam (4.67) (Curve No. 3);
D = Tons of x-per-cent ash coal to produce 100,000,000 B. t. u. in steam (Curve No. 3);
R = Capacity Ratio[2] (Curve No. 1);
S = Pounds of refuse per ton from x-per-cent ash coal (Curve No. 2);
T = Pounds of refuse per ton from 5-per-cent ash coal (160 lb.) (Curve No. 2);
U = Cost of ash handling and removal in dollars per pound.

Formulas, Relative Value Neglecting Investment.—

$$CX = DY$$

$$Y = \frac{CX}{D} \quad\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$Z = Y - (S - T)\,U \quad\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Formulas, Relative Value Including Investment.—

$$CX + \frac{5.13B}{A} = DY + \frac{5.13B}{AR}$$

$$Y = \frac{CX + \frac{5.13\,B}{A} - \frac{5.13\,B}{AR}}{D} \quad\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$Z = Y - (S - T)\,U \quad\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

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[1] Load Factor $= \dfrac{\text{Total steam generated in pounds per year.}}{\text{Pounds of steam generated in maximum hour} \times 8750.}$

[2] Capacity Ratio $= \dfrac{\text{Maximum capacity of boiler plant with 20-per-cent ash coal.}}{\text{Maximum capacity of boiler plant with 5-per-cent ash coal.}}$

Example 1, Where investment cost is not considered.—

When 5-per-cent ash coal costs \$3.00 per net ton in bunkers, and ash handling and removal costs 20 cents per ton, to determine the economic limit of cost for coal having 20 per cent ash:

We have $X=3.00$, $C=4.67$, $D=6.75$ (Curve No. 3), $S=840$, $T=160$ (Curve No. 2), and $U=0.0001$.

Substituting in Eqs. 1 and 2,

$$Y = \frac{4.67 \times 3}{6.75} = \frac{14.01}{6.75} = 2.08$$

$$Z = 2.08 - (840-160) \times 0.0001 = 2.01$$

Similarly, when 5-per-cent ash coal costs \$8.00 per ton in the bunkers, ash handling and removal costs \$1.00 per ton, for 15-per-cent ash coal we have $X=\$8.00$, $C=4.67$, $D=5.73$ (Curve No. 3), $S=530$, $T=160$ (Curve No. 2), $U=0.0005$.

Substituting in Eqs. 1 and 2, $Y=6.52$ and $Z=\$6.33$.

Example 2, where investment cost is considered.—

When 5-per-cent ash coal costs \$3.00 per ton in the bunkers, ash handling and removal costs 20 cents per ton, the load factor is 50 per cent and additional boiler plant would cost \$90.00 per maximum horse power with 5-per-cent ash coal, to determine the economic limit of cost for 20-per-cent ash coal:

We have $X=\$3.00$, $A=0.50$, $B=0.90$, $C=4.67$, $D=6.75$ (from Curve No. 3), $R=0.736$ (from Curve No. 1), $S=840$, $T=160$ (from Curve No. 2), and $U=0.0001$.

Substituting in Eqs. 3 and 4:

$$Y = \frac{4.67 \times 3 + \frac{5.13 \times 0.90}{0.50} - \frac{5.13 \times 0.90}{0.50 \times 0.736}}{6.75} = \frac{10.71}{6.75} = \$1.59$$

$$Z = 1.59 - (840-160) \times 0.0001 = \$1.52.$$

Similarly, where 5-per-cent ash coal costs \$8.00 per ton in the bunkers, ash handling and removal costs \$1.00 per ton, the load factor is 30 per cent and additional boiler plant would cost \$110.00 per maximum horsepower with 5-per-cent ash coal, for 15-per-cent ash coal, we have $X=\$8.00$, $A=0.30$, $B=1.10$, $C=4.67$, $D=5.73$ (Curve No. 3), $\mathrm{R}=0.845$ (Curve No. 1), $S=530$, $\mathrm{T}=160$ (Curve No. 2) and $U=0.0005$.

Substituting in Eqs. 3 and 4, $Y=\$5.91$ and $Z=\$5.73$.

The foregoing methods apply in their entirety only where in using a lower grade fuel it would be necessary to build a complete addition to the boiler plant. In many cases, by changes of a more or less extensive nature to the coal-burning equipment, the desired output may be obtained while using a much lower grade fuel than that for which the station was designed.

Let us consider, for example, a plant located in the lignite regions of the Northwest that is so equipped as to give the desired output when using high-grade Eastern coal but has not a sufficient coal-burning capacity to function satisfactorily with lignite. In such a case it may be easily possible to obtain the desired output with lignite by rebuilding the furnaces and installing new stokers with a much larger grate surface or by installing fuel pulverizing and burning equipment. In a case like this it becomes a matter of comparing the cost of obtaining the desired output with Eastern coal and the present equipment to that of obtaining the same output when burning lignite, consideration being given to the additional fixed charges made necessary by substituting new fuel burning apparatus for that at present in use.

In building a new plant, careful consideration should always be given to the coal available at the locality where the plant is to be built and fuel burning equipment should be installed which would enable the plant in question to deliver the desired output for the lowest cost when both fixed and operating charges are considered.

Having determined the relative value of the coals under consideration, contracts should be placed with those producers whose prices, quality considered, are the cheapest. In distributing the tonnage, consideration should be given to the general reputation and responsibility of the producer and his facilities for carrying out his contract, also to the advantage of having the coal come over a number of lines of railway and from districts so separated that a local interruption to production is not likely to cut off the whole supply.

The purchase and sale of coal is controlled to such a large extent by the type of fuel available in various parts of the country and the diverse needs of different industries as well as the condition of the coal market, that no general system of procedure or form of contract can be devised which will best meet the needs of any large proportion of the coal trade. All specifications should, however, in addition to price, clearly define quality and delivery and the quality demanded should be based on a thorough knowledge of the relative values of the coals available for the plant under consideration.

Given a sample which is representative of a cargo of coal it is an easy matter to obtain a correct analysis and by applying the principles outlined above to obtain a very close estimate of its relative value. The great element of uncertainty lies in the difficulty in obtaining a sample which correctly represents the cargo under consideration. This is especially true when dealing with coals carrying lumps of slate and other foreign matter.

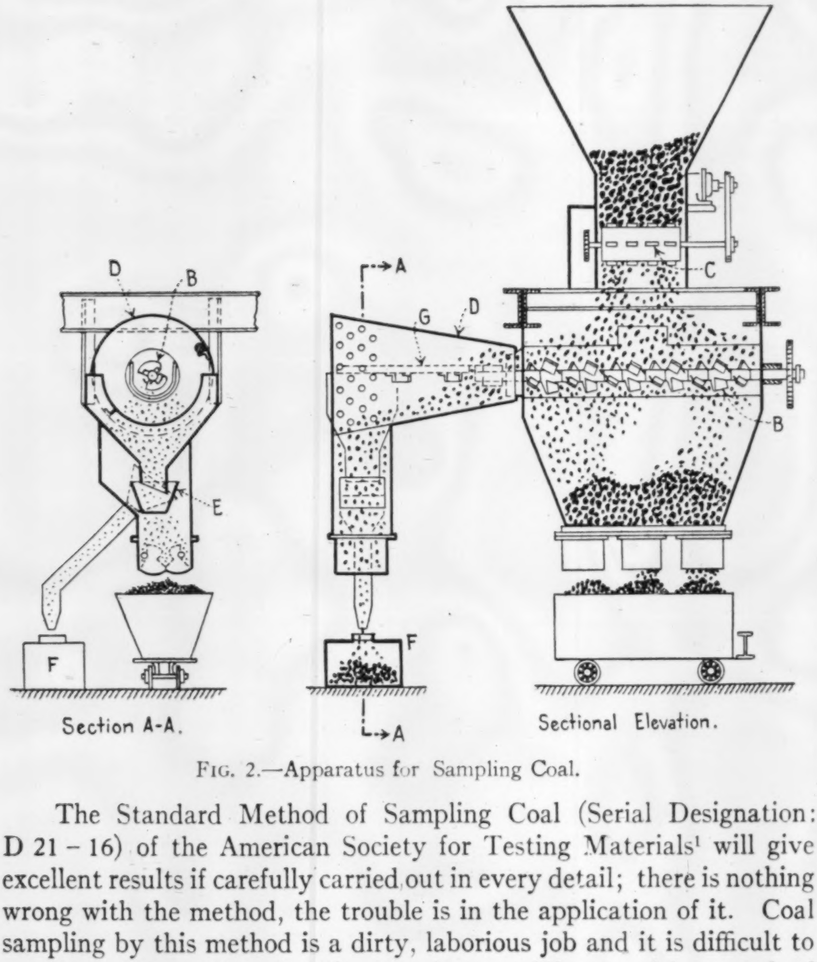

FIG. 2.—Apparatus for Sampling Coal.

The Standard Method of Sampling Coal (Serial Designation: D 21 - 16) of the American Society for Testing Materials[1] will give excellent results if carefully carried out in every detail; there is nothing wrong with the method, the trouble is in the application of it. Coal sampling by this method is a dirty, laborious job and it is difficult to get men with sufficient intelligence who are willing to stick to work of this kind. This difficulty can be best met by the use of some form of mechanical sampler so arranged as to take, crush, mix and reduce the sample, thus eliminating the human element.

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[1] 1921 Book of A.S.T.M. Standards.

Mechanical samplers must of necessity be of many types to operate in conjunction with the coal-handling machinery in various plants. A continuous mechanical sampler which it is believed embodies in a large measure the requirements for accurate sampling is shown in Fig. 2. This sampler consists of a screw conveyor *B* so arranged as to continuously take a sample, the stream of coal being delivered from the crusher *C* at the rate of two tons for a cargo of 1000 tons. This sample is thoroughly mixed and crushed in a rumbler *D* by a pipe *G* loaded with lead from which it falls through perforated openings in the lower end of the rumbler into a pivoted hopper *E* which operates in synchronism with the sampler, so that for 54 seconds in every minute the entire stream goes into the discard and for the remaining time it is diverted to the sample box *F*. The 400-lb. sample resulting from this operation is then reduced to laboratory size by the standard method.

Too much stress can not be placed on the necessity for accurate sampling because no contract for coal can be made where quality is a consideration unless both buyer and seller can agree that the sample taken fairly represents the cargo in question.

While the purchase and sale of coal on the spot market is to some extent necessary on account of the fluctuations in supply and demand, this system is not to be recommended where large quantities are involved because of its demoralizing effect on the continuity of operations at the mines and the loss in efficiency at the consumer's plant due to continual fluctuations in fuel quality.

The character of the provisions in coal purchase contracts have in the past been largely governed by the market conditions at the time the contract was signed. During times of scarcity the consumer is forced to take anything in the way of coal which he can get under any conditions which the seller cares to impose and when conditions are reversed the seller has difficulty in disposing of his output at any price.

In the long run nobody makes any money out of contracts which alternately impose unfair conditions on one side or the other. If the consumer forces the producer to lose money in time of oversupply, he will have to make it up when there is a scarcity, and the producer who imposes on his customers in boom times will probably have no customers when business is slack. The most satisfactory system for both parties to the coal trade is where relations are continued between a producer and his customers from year to year with only such changes in price as changed costs of production may necessitate. Under such conditions a spirit of mutual confidence and helpfulness is built up which is often worth more than the most ironclad agreements.

In any contract, the price having been agreed upon, the most important considerations are quality and delivery.

Quality.—Unfortunately coal as it occurs in the ground is not a pure substance but contains veins or pockets of foreign substances which, if allowed to remain in the coal, materially decreases its value to the consumer. To a considerable extent these foreign substances can be removed by the installation of suitable apparatus at the mine. The apparatus necessary to remove the larger impurities, such as sulfur balls, parting veins and portions of the roof and floor, is very simple and the cost of that degree of cleaning required to produce commercially clean coal is so slight in comparison with the increase in value to the consumer that such cleaning should be insisted on in all cases. In many cases by the use of a more costly system the percentage of impurities can be still further reduced, and where the increase in value due to this additional cleaning is more than enough to pay for its cost, arrangements should be made to have the impurities reduced to as low a point as possible, the price being so adjusted as to be profitable to both parties. Quality can be insured by setting up a standard which, if not met, subjects the coal to rejection, or variations in quality may be adjusted by a bonus and penalty which will indemnify the buyer for his loss due to the coal being poorer in quality than that specified and reward the seller for any gain which the buyer may make due to the quality being better than that specified.

Delivery.—For the best interests of the industrial world deliveries should be made in equal weekly quantities throughout the year, and where the demand varies throughout the year the consumer should, if possible, maintain a storage sufficient to take care of the fluctuations in his demand and the normal fluctuations in delivery due to weather conditions and delays in transportation. Contracts can be written insuring heaviest deliveries at the time of peak demand, and having clauses which guarantee delivery under any and all circumstances. This kind of service however costs money and the consumer must pay well when he demands such service.

Our aim in purchasing coal should not be to get the most coal or the largest number of British thermal units for a dollar, but to get that coal which, when used in the plant for which it is bought, will enable that plant to deliver the required amount of its products for the lowest cost when both operating and investment charges are considered.

[This paper was discussed jointly with the one by Hubb Bell which follows. For this joint discussion, see page 572.—ED.]

FORMS OF SPECIFICATIONS FOR PURCHASING COAL.

By Hubb Bell.[1]

It is becoming increasingly common to purchase material according to an agreement between the purchaser and the contractor which is based on the value of the material for the purpose for which it is bought. In such cases it is customary for the purchaser or the contractor to submit specifications of the material in question, which specifications are agreed upon by both parties interested before the purchase is ratified. These specifications may be a vague understanding between the purchaser and the contractor, they may be a very indefinite statement of the merits of the material in question, but they are coming more and more to be based on scientific and technical data.

In the past, in the development of specifications for material, little attention has been paid to any particular standard for specifications, it being probably felt that each man or concern knew best how to write a specification. In many cases this led to a form detrimental to the purchaser, the contractor, or both. It is therefore thought that consideration should be given to specifications in general, which can then be specialized to meet the particular requirements for each plant. With this in view, a detailed outline is herewith given on the methods of preparing coal specifications. This topic is treated as a comprehensive standardization of the method of preparation of specifications and is also given as a guide in a field in which the uses of specifications are still in the process of development.

It is impossible to formulate a universally applicable specification which will embody the requirements for all plants; each power plant or steam producing plant is essentially peculiar to itself; consequently, any expression of specifications must emanate from the plant.

A satisfactory coal contract should describe as far as possible the sources from which the coal is to come; the coal should come from the same region and bed. In such case the heating value varies proportionately to the ash content which therefore becomes a measure of heating value. The valuation of coal is predicated upon its impurities. If a bonus and penalty contract is confined only to the ash content of the coal and the regions or beds are specified from which the coal is to come, practically everything else in the coal follows. When coal comes to a plant from different beds or regions, then determinations of analysis other than the percentage of ash are necessary. It is recommended that specifications on an analytical basis, involving a premium and penalty, be based only on the ash content of the coal, and that penalties and premiums be levied in proportion to the freight paid on that particular coal. Any premium or penalty should be so arranged that the buyer is indemnified for his loss, due to the quality being below specifications; and the seller is compensated for any gain which the buyer realizes, due to the coal being better than specifications.

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[1] Chemist, United States Testing Co., Inc.

In handling the complaints arising from shipments of coal, it has been found that the majority of such complaints were caused by inaccurate sampling. In the chemical analysis there is little chance for error provided the work is done in accordance with the Standard Methods of Laboratory Sampling and Analysis of Coal of this Society. The weakest point in the present system of testing coal is the method of taking the sample and preparing it for analysis. The effect of improper sampling of a lot of coal—such as a pile, a car, or barge load—is so evident that proper sampling is now realized to be the most important feature of coal testing. Poor sampling is general; it has been found in plants that consume thousands of tons of coal monthly, in plants where coal has been bought on specification basis for several years, and in plants where skilled chemists are employed. Local conditions and facilities to some extent govern sampling, but the principles of proper sampling may be followed out at any plant whether the coal be received by barge, railroad car, or truck. Should modifications of the Standard Methods of Sampling Coal of the Society be necessary, the variations should be drawn up by agreement between buyer and seller when the contract is consummated.

The seller should, barring providential causes, bind himself to ship the specified quantities and qualities at the specified times.

The buyer should bind himself to take and pay for the coal if it is shipped in accordance to contract as regards quantity, quality and shipment.

The above makes possible the adoption of specifications when and as the various details may be agreed between the two parties.

A RECOMMENDED SPECIFICATION CONTRACT FORM FOR THE PURCHASE OF COAL FOR USE IN STEAM POWER PLANTS.

AGREEMENT entered into this .... day of ...., 19......, between ...., a corporation organized under the laws of the state of ...., located at ...., hereinafter referred to as the Seller, and ...., a corporation organized under the laws of the state of ...., located at ...., hereinafter referred to as the Buyer.

The Seller hereby agrees to sell and ship, and the Buyer hereby agrees to purchase and accept, between the .... day of ...., 19........ and the .... day of ...., 19........, the quantity and kind of coal and at the price hereinafter stated upon the terms and conditions herein contained, to wit:

QUANTITY..
RATE OF SHIPMENT..
KIND AND DESCRIPTION..
PRICE..
TERMS OF PAYMENT..
SOURCE: The source of the coal herein specified shall be as outlined below:
Name of Mine or Mines..
Railroad on Which Mine or Mines Are Located...

QUALITY.

The Seller agrees that the average composition of the coal, as determined by chemical analysis upon dry samples, obtained as hereinafter provided, shall be:[1]

	MAXIMUM.	MINIMUM.
Volatile Matter, per cent	....	....
Fixed Carbon, per cent	....	....
Ash, per cent	....	....
Sulfur, per cent	....	....
British thermal units	....	....
Fusing temperature of ash, deg. Fahr.	....	....

PREMIUM AND PENALTY.

Payment for coal shipped shall be made on the basis of the price named in this contract for the coal the Seller agrees to furnish, corrected only for the variation in the ash content.[2]

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[1] These requirements should be based on previous years' experience, or based on analysis of sample shipments, after boiler tests.

[2] This should be a negotiation between buyer and seller based on local conditions and the geographical location of the plant, that is, the percentage of penalty for an excess ash over and above the break-down standard of the plant should be in proportion of a tonnage haul as applied to a distance.

SAMPLING AND ANALYSES.

All samples shall be collected, prepared and analyzed in accordance with the requirements of the Standard Methods of the American Society for Testing Materials.[1]

TERMS AND CONDITIONS.

1. Prompt payments on their due date at the Seller's office in .... is of the essence of this agreement. All overdue accounts shall draw interest at the rate of 6 per cent per annum. Default on the part of the Buyer, in any installment payments, or any failure to accept any installment delivery shall, at the option of the Seller, operate as a breach of the entire order, and shall entitle the Seller to cancel the entire order without notice, and a waiver by the Seller of any default in either of these respects shall not operate as a waiver of its right to cancel the order because of any subsequent fault either in Payment or acceptance of delivery on the part of the Buyer. If the credit of the Buyer shall at any time in the judgment of the Seller become impaired, the Seller shall have the right to require payment in advance before making further shipments, or at its option have the right to elect to cancel any unfulfilled portion of the order.

2. Railroad scale weights at point of shipment are to be accepted as correct and are to govern all settlements when the price stipulated herein is on basis of "f. o. b. cars at mines," and the certificate of the Railroad Scale Master shall be conclusive evidence of the weights and the delivery of the coal to the Buyer. In the case of all shipments on the basis of f. o. b. mine price the shipper's responsibility ceases and the coal shall then in all respects be at the risk of the Buyer. Where the Seller agrees to deliver the coal covered by this order over railroad piers, and on the basis of "alongside" or "delivered" price, weights as furnished by the railroad at the loading piers are to be accepted, and are to govern settlements.

3. The Buyer agrees that the Seller shall not be held liable for any damages for failure to deliver any or all of the within mentioned coal if such failure is due to providential causes, war within the United States or with another country, shortage of suitable cars, accidents, strikes, lockouts, or similar occurrence beyond the control of the operator of such mine or mines, with whom the Seller may arrange for the shipment of the coal on this order; similarly for failure to supply in the event of such failure being due to embargoes, interruptions of transportation, by congressional or legislative action, or by legal proceedings, or to any cause whatsoever beyond the Seller's control.

(*a*) The Seller is the owner or exclusive sales agent of the mine or mines at which the coal sold hereunder is produced, or prior to or simultaneously with the execution of this agreement has entered into a written contract for the purpose of a sufficient quantity of coal from such mine or mines to fulfill the obligations of the Seller under this agreement;

(*b*) The name of the owners and location of such mine or mines is stated in this agreement;

(*c*) The Seller gives the Buyer written notice within five days after such occurrence of the exact nature, extent and probable duration thereof with sufficient detail to enable the Buyer to verify the same;

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[1] These methods were formulated and adopted by a joint committee of the American Chemical Society and the American Society for Testing Materials. Variations of the A.S.T.M. methods should be drawn up by agreement between the Buyer and Seller when the contract is consummated.

(*d*) The Seller reserves the right to incur obligations for the sale of its coal from the mines above mentioned during all periods when deliveries required under outstanding obligations do not in the aggregate exceed the physical capacity of said mines.

(*e*) In the event of contingencies or causes restricting the production or shipment from said mines, the Buyer shall be entitled to receive hereunder, in any one month, only that proportion of the tonnage herein contracted as actual total shipments in available coal car equipment bear to (1) rated capacity of said mines (as determined by Railroad Car Distribution Rules) or to (2) physical capacity of said mines in case rated capacity shall have been reduced by contingencies or causes of the character herein referred to; and where contingencies or causes affecting delivery of coal, affect deliveries to other customers, as well as deliveries to Buyer, the Seller agrees to pro-rate available facilities for delivery among all of its customers so affected, including Buyer, in proportion to the amount of coal that each is entitled to receive.

4. In case of strikes, fires, accidents or causes beyond the control of the Buyer which wholly or partially stop the works of the Buyer, shipments contracted for shall be suspended or partially suspended during the period of such interruption upon written or telegraphic notice to the Seller.

5. The price named in this order is based on the present mining rate in the district where the mine or mines producing the herein mentioned coal are located, and any increase or decrease in the present cost of production at said mine or mines due to changes in the scale of wages of all labor, of whatever kind, which enters into the production or preparation of the said coal or to taxes or imposts or to any federal or state legislation, shall be added to or deducted from the price fixed herein on any and all tonnage shipped hereunder and affected thereby. The price fixed herein is based on the present freight rate, in the event of this order including such freight, and the Buyer shall pay any increase over the present freight rate, and shall be credited with any decrease on shipments made during the life of the contract specified herein.

6. In case either the Buyer or Seller makes default in any of the terms or conditions of this order, waiver of such default by either party shall not operate as a waiver of any subsequent default.

7. Notice sent by telegram or registered mail, addressed to the party to whom such notice is given, at the address of such party stated in this agreement, shall be deemed sufficient written notice in any case arising under this agreement.

8. No understandings, agreements or trade customs not expressly stated herein shall be binding on the parties in the interpretation of fulfillment hereof unless such understandings, agreements, or trade customs are reduced to writing and signed by these respective officers.

IN WITNESS WHEREOF, the parties hereto have caused this agreement to be executed in duplicate by their respective officers duly authorized the day and year first above written.

....Seller

By..

....Buyer

By..

DISCUSSION ON COAL PURCHASE SPECIFICATIONS

Mr. Hood. MR. O. P. HOOD (*presented in written form*).—Mr. Ricketts' paper shows very well the two principal kinds of use that engineers make of coal analyses: first, in a general study of types of coal available, and second, in defining a particular fuel.

I have been impressed by the frequency with which the partly informed assume that engineers scan a list of coal analyses and expect to unerringly select the particular coal which, inflicted upon the operating force, is to yield maximum efficiency. Having set up this straw man, it takes little application of experience to reduce the error to a non-coherent mass easily blown away. The unwarranted conclusion is then drawn that analysis is of very doubtful value and unworthy of a place in a business man's contract. It is nearly useless to argue with those who have so much to learn. The combustion engineer never asserts that analysis tells all about a coal. He confidently asserts, however, that it is one of the great helps in his business, and proceeds to use it intelligently, aware of its limitations and occasional deceptions.

It is a significant fact that in those industries where coal forms a large part of the manufacturing expense (something over 60 per cent in the manufacture of electric current) coal analysis is depended upon for certain things, while in those industries where coal is a 2-per-cent item there lingers a belief that specifying coal quality by analysis is a doubtful refinement.

Having determined the type of coal desired, and defined it as well as may be by quoting certain analytical characteristics and limits, it is to be noted that the paper asserts that the value to the user is determined on a scale calibrated by actual experience when the analysis of representative samples is known. This is the real engineer's use of analyses. Even where less information is available, this is the ideal he has in mind. It is probable that with coals from the same district, and coming within the analytical limits specified, the percentage of cases where seriously discordant results would be obtained would be extremely small. These exceptional cases are too often enlarged upon and given as an excuse for a cynical attitude toward coal analysis.

Mr. Hood. It is to be noted that Curve No. 3 of Fig. 1 of the paper shows that an increase in ash from 16 to 17 per cent is more than twice as effective in reducing value as an increase from 6 to 7 per cent, justifying a rapidly increasing penalty for poorly prepared coal.

Human factors are not included in the formulas derived. With coal of variable quality, anxiety and irritation in the operating force is reason for further penalizing poorly prepared coal.

Mr. Bell's proposed specification is valuable in its simplicity. Coal specifications with others are apt to grow by yearly accretions until they become unwieldy and sometimes unintelligible. The present tendency toward simplification is much needed. Mr. Ricketts assumes that a rational basis for coal specifications depends upon knowing the coal quality in terms that can be expressed in figures. This is analysis.

The large consumer of coal is able to employ talent to make tests of his plant performance, and construct the curves from which these equations come. But the great body of coal purchasers are unable or unwilling to go into the problem so deeply. What is done with the coal industry is not going to be determined by the few hundred purchasers of very large tonnage, but rather by the multitude of small users who have a very real interest in coal quality. Their interests seem to demand some sort of national fuel inspection that will certify to coal quality, and this presents a different problem in sampling and analysis.

There is another phase of this question which must be considered in developing standards in connection with coal purchase. We have been in the habit of thinking of this matter as of interest only to the buyer and seller of coal, that whatever is done is to facilitate either the commercial or the technical aspect of a transaction between two people. There is need for an enlargement of this idea, and an appreciation of the fact that there is a national aspect to coal problems. The systematic buying of coal on a quality basis is desirable from the standpoint of the community as a whole. Other countries are finding it necessary to give careful consideration to the extent and character of their fuel resources, and are making efforts to have each fuel used for that purpose for which it is best suited. Any less advantageous use is recognized as a community loss. In our own country, price has already restricted the use of prepared sizes of anthracite coal to domestic service. Our choice coking coals, however, are still used for steam making, for which purpose coal of less special utility would do. Restriction of the use of fuel oil to naval and marine service, where its special characteristics are of greatest value, is possibly within

Mr. Hood. sight of the present generation. The use of our special grade fuels for purposes that can be met by fuels of less specialized quality is something that should not, and cannot, continue always. While the evolution due to commercial practice will, in the long run, furnish a solution, there will be many times when there will be little to determine choice between fuels, and at such times these general arguments of community benefit may well furnish the determining factor. The careful definition of coal quality which is the essence of the specification method, is an aid to this discriminative buying of coal. Much the same argument may be made for different grades of the same type of coal. So long as there is no adequate differential in price between low-ash and high-ash coals of the same type, there is no sufficient inducement to the engineer to make the greater initial investment necessary to handle poorer coals, although it is to the advantage of the community to have the poorer as well as the better coals used. It seems evident that in the long run there is an economic waste whenever a superior material is unable to obtain a price comparable with its worth, or whenever a poor material, by habit or custom, receives a price beyond its real worth. Engineers know that poorer grade coals can be burned with high efficiency, but the mechanical equipment must be adapted to such conditions, and there must be a uniformity of quality.

Coal specifications and analysis lead to a more careful description of the fuel, and to a closer differentiation of one fuel from another, and are thus a matter of community interest. It is believed, therefore, that the buying of coal on a quality basis is a practical conservation movement with a national significance quite apart from any advantage of the method in the individual transaction.

An even more important national aspect is connected with the national defense. If, in time of stress, it is necessary to accelerate industrial productivity, it seems absurd to expect to do this by increasing the tonnage of rock shipped with the coal. Mr. Ricketts has shown that, with a given equipment and adjustment, an increase in the quantity of ash accompanying the coal decreases the value a surprising amount when it must be used in an unchanged plant, and poorly prepared coal may, at a critical moment, clog the furnaces of industry so as to make increased production impossible. This condition actually happened during the late war. The country was beguiled with the record of increasing tonnage at a time when the total potential heat output was probably reduced. Some measure of control over coal quality became imperative, but there was not developed a satisfactory solution to the problem. The lessons learned during

Mr. Hood.

the war make it evident that in case of a recurrence of trouble early consideration must be given to the maintenance of coal quality. But we do not have the necessary mechanical equipment or standards for doing this, and a workable system cannot be produced on short notice. It cannot be done by purely administrative processes. It requires machinery, development and experience, and this should be in course of development now. It seems strange that an essential raw material, such as coal, should have escaped for so long a regulation of quality, when many other products such as wheat, cotton, meat, and other food products require quality determination. There has been no lack of suggestion as to the need of discovering coal quality, and impractical legislation has frequently been proposed. A satisfactory system of inspection cannot be built upon visual inspection. There must be an immense amount of righteous sampling. The methods and standards now available are impracticable for application on a large scale. I need only refer to the standard method of taking coal samples promulgated by this Society and the U. S. Bureau of Mines, to illustrate this point. The sampling method is a hand method, and comparable with trying to unload a cargo of coal with a wheelbarrow. Some larger conception of our sampling problem must take hold of our imagination and be reduced to practice.

A study of the whole question of national inspection of coal leads one to the conclusion that the key to the problem is that of obtaining a just sample under the present limitations of coal handling and transportation methods. Sampling and analysis must cost very much less than it does now. It is believed that if this sampling problem were solved the other problems connected with national coal inspection would be found to be possible of solution.

There are some analogies that are useful to consider. Iron ore is all sold on a quality basis. Every car is sampled, and the price paid depends upon the analysis. Coal has been worth more per ton than iron ore on several occasions. This sampling of iron ore is done while it is on the car, and not while it is being transferred from one container to another, as is the practice in sampling coal. It seems impracticable to sample coal at the point of origin, because of the great number of mines, and equally impracticable, because of the greater number, to sample the coal at the point of delivery. In carrying coal from the mine to the user a large percentage of coal flows through certain narrow transportation gateways. It would seem as though at these points of greatest concentration the sampling in a national system should be done by some mechanism comparable in extent and conception to the coal handling devices that have been developed for

Mr. Hood. loading and unloading coal. Following this line of thought, the U. S. Bureau of Mines is building an experimental unit to test the feasibility of this key problem, the taking of a just sample from railroad cars without unloading a car or breaking the train, and in such short time as will not interfere in the least with present transportation practices. Should this come to a successful conclusion, it would appear to be necessary for this Society to broaden its recommendations concerning the standard method of sampling coal.

Mr. Barrington. MR. W. D. BARRINGTON (*presented in written form*).—There are many advantages and disadvantages for the purchase of coal on a specification basis to the buyer and seller alike, and Mr. Ricketts' paper contains many points which should assist in eliminating some of the disadvantageous features.

The illustration given for selecting coals suitable for use at a particular plant explains in considerable detail the general procedure followed by several large public utility steam plants to obtain at minimum cost the most efficient plant operation with assurance of necessary coal supply. A point for discussion is the limits of the field to which this method is practical and economical for application. The buyer without the facilities for properly carrying out the required test work might well afford to purchase coal from a seller maintaining a technical staff and leaving the application of suitable coal up to their engineers.

Mr. Ricketts also sets forth the necessity of devising standard automatic methods for the sampling and preparation for shipment of same to the laboratory, and these methods should be given further consideration by the Society.

To my knowledge the seller is not adverse to selling coal under an equitable specification contract, but such specification contracts have not come to my attention, and Mr. Ricketts' paper should be an inspiration to those favorable to the specification contract method of purchasing coal in preparing rational and equitable contracts.

Mr. Bell has set forth several important features in the preparation of an equitable coal contract to those interested in this problem. Many points in the "Recommended Specifications Contract Form" should be given serious consideration for revision, and the form made to cover "line and tidewater delivery."

Mr. Job. MR. ROBERT JOB.—Each one of the speakers has emphasized the importance of the subject that we have before us to-day, and everyone of us who has anything to do with the use of coal thoroughly realizes this. Each one of the speakers has mentioned the necessity of getting accurate samples of the coal, and special mention has been made by Mr. Ricketts as to the method which he has used in obtaining samples. I have been interested also in noting the statement made by Mr.

Mr. Job.

Hood of the difficulty of getting an accurate sample by any of the methods in use at the present time, due to the fact that the methods are very cumbersome and that it is very difficult to get a sample which accurately represents the quality of the coal, and there is difficulty particularly in getting a good representative sample within a reasonable time, so that no inconvenience would be caused by waiting for the unloading of the shipment. It occurs to me that a simple method which we have had in use for a number of years upon the Lehigh Valley Railroad may be of interest, and I will describe it briefly. A great deal of our coal is obtained in carload lots, and our plan has been, in getting the sample, to take a boiler flue about 2½ in. in diameter, place a solid plug in one end, so that the tube could be driven down into the coal—the tube itself is about five feet long. There are two ⅝-in. holes near the top, through which a ½-in. bar about 18 in. long can be placed, so that while the tube is being driven down into the coal, a one-quarter turn can be given to the tube after each blow. By means of this simple arrangement we have found it is possible to drive the tube down from top to bottom of the car through any pieces of slate; it cuts out the core, not like a diamond drill, but quite satisfactorily. After the tube has been driven to the bottom of the car, we draw it out carefully by means of the iron rod at the top and then tap the tube lightly with a hammer so that the coal inside of the tube is run out into a clean iron bucket. This sample is taken from about five or six different parts of the car, and of course it could be taken from as many points as was desired. After the sample has been taken, it is pulverized and thoroughly mixed and then quartered down, and the usual sample for analysis is taken. A sample of this kind can be taken in a very short time with the ordinary labor available, and we have found that it is possible to get a very fairly representative and reasonably accurate sample by this means.

There was another point that occurred to me in connection with Mr. Ricketts' paper where he speaks about the necessity of having coal of which the ash has a high fusing temperature. A good many of our specifications have not taken any account of the fusing temperature, but those of us who have had a good deal to do with the burning of coal, particularly in locomotive service, know how necessary it is to have a coal which will not clinker badly. I remember an instance that occurred some years ago in which we found that a locomotive was stalled in a run of less than ten miles with a coal that had only 4 per cent of ash. That seems almost incredible, but the reason for it was that in that particular instance the ash was exceedingly high in iron and had a very low melting point, and as a result a blanket was formed over the body of the coal and the passage of air through

Mr. Job. the coal was entirely shut off. Furthermore the red hot particles of this plastic ash were carried forward and caught by the hot flue sheet, and in that way what the enginemen term "sulfur lumps" were formed, until the openings of the tubes were completely closed. At other times we had coal which ran up to 20 or 25 per cent in ash which caused no trouble whatever of this nature. The reason was that the latter coal happened to be a white ash that had a very high fusing point, and the ash simply blew through the flues and did not cause any trouble. Instances like this give some indication of the importance of the subject and of making careful tests and careful selection of the supplies of coal as they come in. I have been extremely interested in hearing not only the papers but the remarks made by Mr. Hood and by the others in connection with the subject, and for one I am very well satisfied in my own mind that Mr. Hood's statement is entirely correct, namely, that our present methods of sampling will have to be modified very decidedly before they are really accepted as a satisfactory basis for practical work.

Mr. Brady. Mr. William Brady.—Referring to the method of sampling coal as described by Mr. Job, I desire to state that several years ago I tried to sample coal on cars by this method.

If the tube could be made to cut out a section of coal from top to bottom of the car, the method would be ideal. The trouble we experienced was in making the tube cut out the section of coal. We very seldom obtained a depth of coal in the tube equal to one-half the depth of coal sampled. Many times there was less than a foot of coal in the tube after driving the tube through three feet of coal. Frequently there was no coal at all in the tube, when the tube was withdrawn.

Mr. Job. Mr. Job.—It has to be drawn out very carefully; some of the coal is in a loose condition and there may be voids, and in driving it down there may be a good many places where the coal will be easily taken out of the tube; consequently the tube must be drawn out very carefully, without any shock. If that is done, I think there won't be any great trouble in getting a reasonably full tube of coal. I have used this method on regular run-of-mine coal and also lump coal; most of it has been run-of-mine coal.

Mr. Hood. Mr. Hood.—I would like to say that the U. S. Bureau of Mines has made some experiments on that line, not only with dry digging but with a hand operated augur, and it was felt that the method was not of universal application, at any rate, and when one compared the volume occupied by the supposed core with the actual amount of coal obtained, there was a feeling that we had a pretty good sample from the few inches of coal on top and very little from the bottom.

MR. BARRINGTON.—Relative to the fusibility of ash in connection with Mr. Job's experience, apparently delay in service was attributed to the low fusing point of the ash. Our experience has shown that too much weight is placed in ash fusibility tests, as determined in the laboratory, when diagnosing furnace operating results. Many complaints on clinkering, which the consumer attributed to the fusibility of ash, having received laboratory reports, have been corrected by proper handling of the fires. A recent experience on a Southern railroad with coal having an ash fusing at a low temperature illustrates this fact. Our testing department representative, sent to investigate a strenuous complaint on clinker, made locomotive trips eliminating clinkering troubles by installing ordinary correct firing methods. Before attributing clinker troubles to fusibility of ash it might be well to experiment with operating methods. **Mr. Barrington.**

MR. JOB.—May I ask Mr. Ricketts how he arrived at the temperature of 2450° F., as the ash fusing temperature? **Mr. Job.**

MR. E. B. RICKETTS.—That was determined by a long series of boiler tests, using coals having different fusion temperatures. I ran a set of tests that took me about three months, running on one coal continuously for a week, under as nearly the same conditions as possible, except that the coals had different fusing temperatures of the ash, and the results of those tests were published in the Prime Movers Committee report of the National Electric Light Association in 1916 and were available there. **Mr. Ricketts.**

We have had practically no trouble from coals over 2450° F. fusion temperature. Now that point as a low point in the fusion is, I think, pretty well applicable to coal from the Eastern Pennsylvania semi-bituminous district. During the present trouble which we are having in the coal game, we have been buying a great deal of coal coming from the Pocahontas field. Most of this coal will run under 2300° F. fusion; it is not giving any serious clinker trouble. The characteristics of the clinker from the Pocahontas coal are very different from those of the Eastern Pennsylvania district. The gases in the ash have a tendency to bloat the clinker and make it brittle and easily broken down; whereas a coal of the same fusion point from Eastern Pennsylvania would cause serious trouble. I am not quite as confident on the fusion point game as I was some time ago. I think that we have got to get more data than we have on correlating the fusion temperatures and the furnace performance of coals from different districts. Until recently, as I have said, my experience has been entirely confined to coal from the semi-bituminous Pennsylvania districts, and I am learning something new from the Pocahontas field.

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